# Application of 3D Laser Scanning for the Digitization, Design, and Analysis of a Multistoried Building

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***Submitted :*** 08-03-2021

***Revised :*** 30-09-2021

***Accepted :*** 11-10-2021

## ABSTRACT

Laser scanning is a fast-developing technology that collects millions of points and creates a framework within a few minutes, generating a point cloud of the structure. Laser scanning is a relatively new but rapidly evolving technology. This research used modern models of laser scanners (and their accompanying software) that are capable of accurately capturing and aligning point clouds. Consequently, the laser scans have precisely captured the current geometry of each structure, which is irregular in many cases due to inherently complex geometry, anomalies during the original construction, aging, deterioration, and structural damage. As the exterior and interior components of the structures were scanned, the point cloud became a digital 3D image of the historical building, which can be virtually toured from the inside and outside. A four-story public building was scanned using a 3D laser scanner to generate architectural and structural drawings of the response to an earthquake. The application of passive control using a damper with the laser scanner has been modeled in this study. The results show that this technique provides the best outcomes for reducing seismic damage collapses.

**Keywords:** 3D Laser scanner; Passive Control System; Seismic Design; Finite Element Methods.

## INTRODUCTION

3D laser scanning is an innovative technique for acquiring the precise size and shape of an object as a 3D image. This method gathers data, including hidden shapes with complex geometries, and provides digitally improved quality and additional specifics of the scanned 3D objects. It generates a digital replica of real-world objects, according to the user's requirements, that can be altered and printed.

Generally, in the 21st century, technologists are utilizing such innovations in a reverse fashion: 3D scans or drawings are used as input to computer-aided design (CAD) and 3D printing slicer programs, which are usually compatible with 3D scanner files. The process of gathering and combining individual scans as a 3D scanning network was described by Bhatti et al. (2021) and Ebrahim (2015).

The FARO Focus scanner calculates the as-built state of heritage sites, auditoriums, historical buildings, palaces, temples, art museums, and many other structures. Karan Kamani (2020) reported that it is used in building documentation and topography.

Several other similar works have been reported by Shan et al. (2014) in which 3D scans were used in the restoration of ash-Shafei Mosque, the most significant mosque surviving in Jeddah, in a project that was launched in 2011 under the Al-Turath Foundation and Historic Jeddah Municipality and completed in 2016 (Saudi Commission, 2017). Furthermore, other studies used laser scanning for structural evaluations related to storm and earthquake damage for structures in Uzbekistan, as well as California, USA (ICOMOS, 2011; Mosalam et al., 2014).

## Passive Control System

Today, concrete is an extensively used material in the application of innovative techniques, as studied by Wahab et al. (2021). The structural design methodology for seismic response control is broadly accepted and applied in civil engineering. Recently, attention has been given to the improvement of dampers and control techniques for structures like passive control systems, active control systems, and semi-active control systems, giving importance to enhanced seismic responses of bridges and buildings. A passive control system does not need a power supply, whereas active control systems do need an external power supply. Serious efforts are underway to shift the structural control idea into practical expertise, which is integrated with the structures (Bhatti AQ, 2013; Heysami A, 2015).

Dampers are categorized according to their performance as friction, mass dampers, viscoelastic, metal (flowing), viscous, and shape memory alloys. Figure 1 shows various dampers in use, namely, a friction damper in retrofitting, a PVD damper, and a viscous damper. Among the advantages of using dampers is that they are easy to install and replace, and they coordinate well with other structural members (Bhatti AQ, 2016).

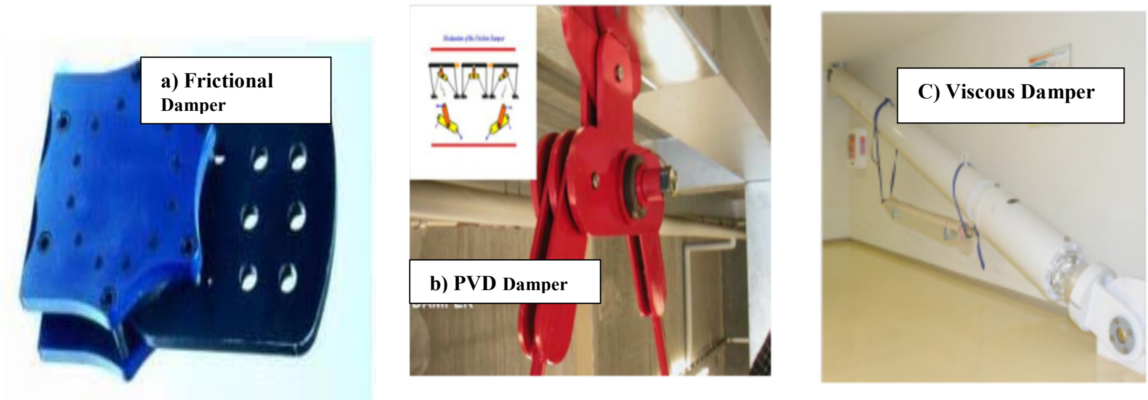



Figure 1: Various dampers in use: a) a friction damper in retrofitting, b) a PVD damper, and c) a viscous damper

Typically, forces acting on the structure, such as earthquakes, may cause unwanted vibration. The seismic waves generated by earthquakes cause a building to sway and fluctuate in several ways, varying based on the frequency and control of ground motion and the height of the building. In fact, the first specific damping mechanisms for earthquakes were not established until the late 1950s. Nevertheless, high-rise and leaning buildings may suffer natural frequency fluctuations depending on changes in the ambient temperature, wind speed, and relative humidity, which means they need a detailed design.

## Earthquake Hazard in Saudi Arabia

In Saudi Arabia, the earthquake hazard is typically categorized as medium, as shown in Figure 2. There is a 10% probability of theoretically destructive shaking in the project area in the next 50 years. The earthquake's effects should be studied in all phases of the project. However, in Madinah, the earthquake hazard is classified as low within the Kingdom of Saudi Arabia (KSA) Earthquakes Regions; specifically, there is a 2% chance of damaging by an earthquake.

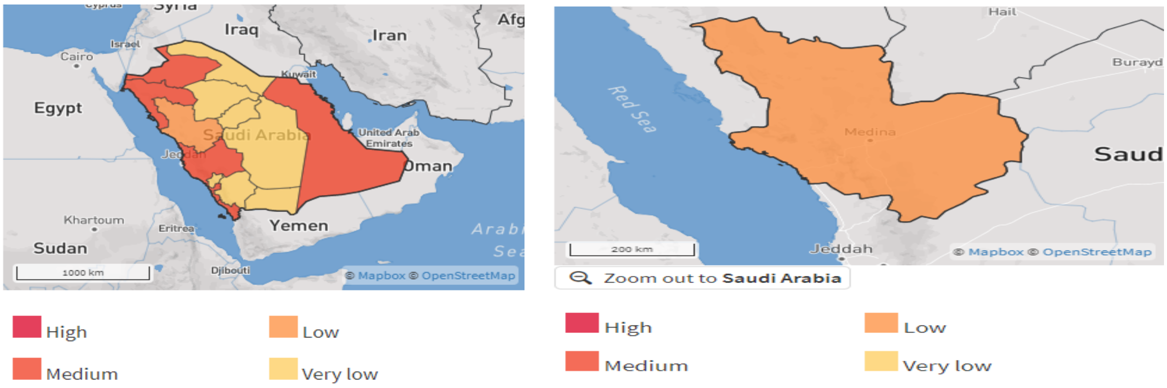



Figure 2: Saudi Arabian Earthquake Regions

On January 16, 2018, the city of Madinah suffered a 2.5 magnitude earthquake, according to the Saudi Geological Society, but there were no reports of damage from the earthquake. The earthquake epicenter was 14 km northwest of Madinah at a depth of 7 km below the surface.

Every year, earthquakes cause thousands of deaths and a massive loss of property worldwide. There is a need to take adequate measures to minimize deaths and damage to property depending on a given area's seismicity. The purpose of this study is to find the best technique for reducing seismic damage to a building by considering the responses of a scale model of the building to the generated waves. Methods for reducing the damage by an earthquake are also analyzed, and the Faro 3D 150-S laser scanner is used for scanning purposes to assess the building's data.

## Description of the Proposed Building for Laser Scanning

Figure 3 displays the Faro 3D 150-S laser scanner equipment used in this study for assessing data. Figure 4 shows the building selected for assessing data. Structural damage represents the degradation of the building's structural support systems, such as walls and frames.

The investigated structure is an engineering building located at an Islamic university. The building has four stories with a typical height of 24.39 m, and the plan area of the building is 29.70 m x 29.70 m. The building has a reinforced concrete frame and a precast hollow core unit lab system at different floor levels. It houses elevators, classrooms, labs, and offices. The local seismic zone of the building is located in 2A, according to UBC (1997). The concrete design is based on ACI-318-02 and all other relevant ACI codes, as well as the live loads and wind loads, are based on ASCE 7-02. According to the available design data, the strength of the concrete is 32 MPa, and the reinforcement is 420 MPa (Varum et al., 2013).

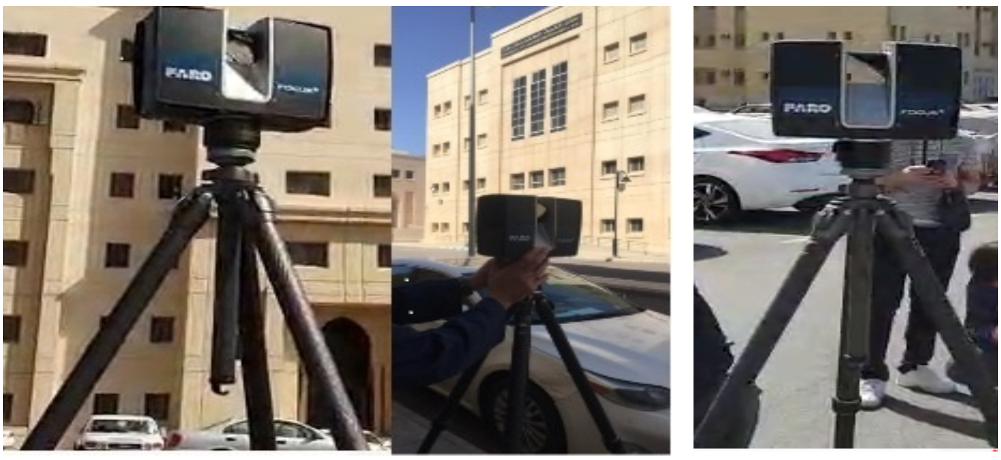



Figure 3: The Faro 3D 150-S laser scanner equipment used in this study for assessing data

Figure 4: The building with front elevation selected for assessing data

## Methodology for the 3D Laser Scanner Setup

First, the tripod was set up, and the scanner was mounted onto the tripod. The SD card and supply power were then inserted into the scanner. The scanner was switched on, and the scanning parameters were set according to the scanning object. Then, the scan was started. Once the scanner completed the scanning process, it was powered off. The Faro 3D 150-S laser scanner is shown in Figure 5 (a). The checkerboards used to ensure the Faro 3D 150-S laser scanner precisely scanned the object and assessed the building data are illustrated in Figure 5 (b).

5 (a) 5 (b)

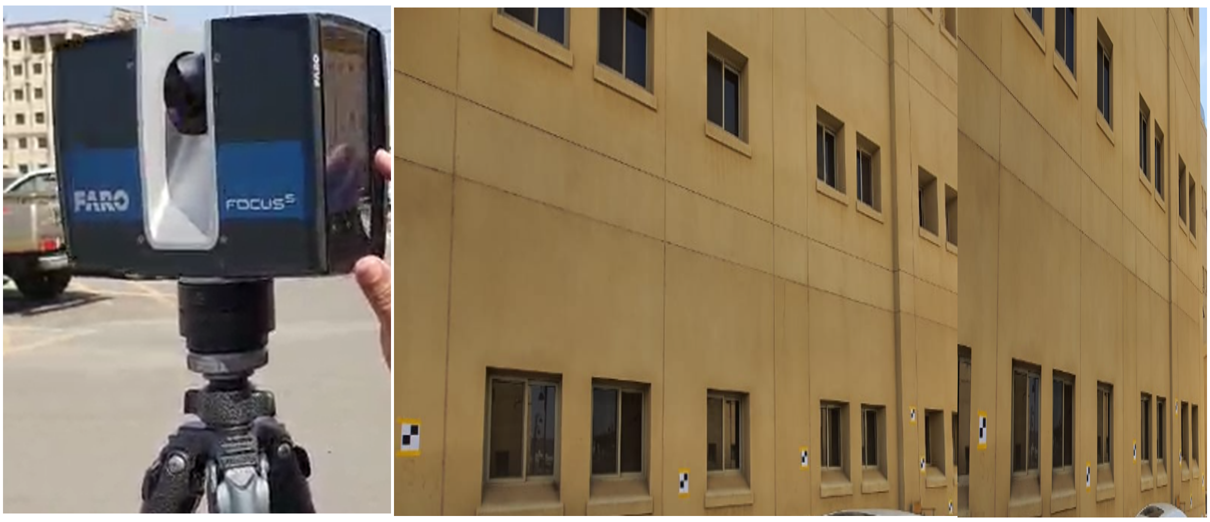



Figure 5 (a) shows the Faro 3D 150-S laser scanner, and Figure 5 (b) shows the checkerboards used by the Faro 3D 150-S laser scanner for assessing the data of the building.

Figure 6 shows the point cloud dimensions generated by Autodesk ReCap Software, and Figure 7 depicts the point cloud dimensions developed by Faro Scene Software. In previous studies, Wahab et al. (2019) and Bhatti (2016) carried out digitization and 3D laser scanning with finite element modeling for historical structures and monuments in Saudi Arabia.


Figure 6: The point cloud dimensions captured by Autodesk ReCap Software[*]


Figure 7: The point cloud dimensions captured by Faro Scene Software [**]

The point clouds were then converted into architectural and structural drawings of the building (see Figures 8, 9, and 10).

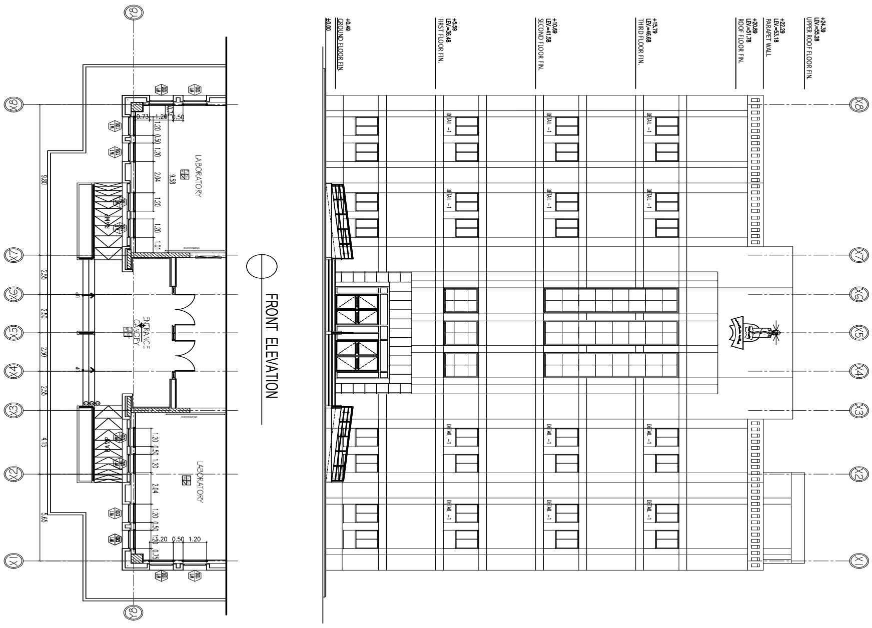


Figure 8: Front elevation of the building

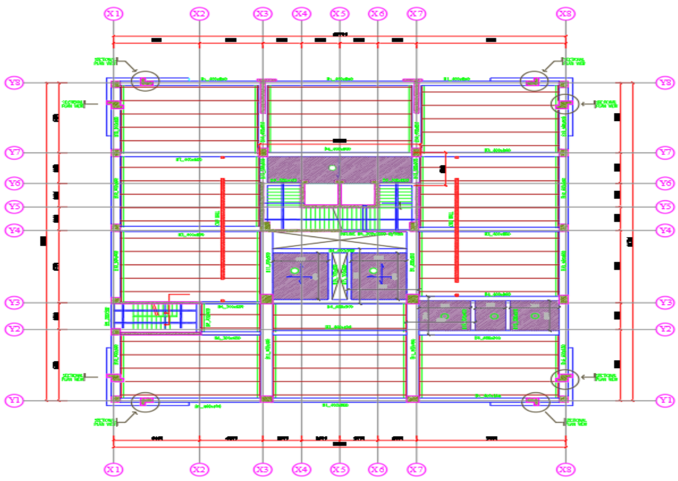


Figure 9: The building's ground floor plan

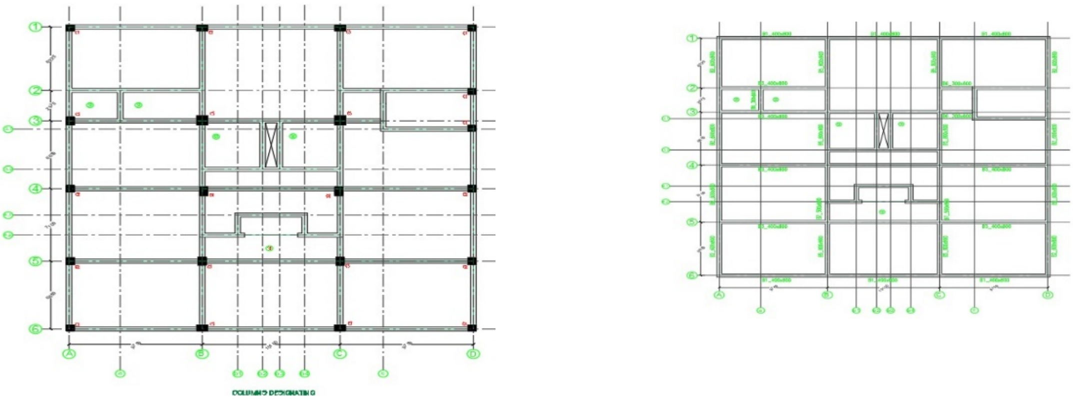


Figure 10: Column and beam positioning

## Simulation Models

It is essential to specify the codes used in the project to design and plan the simulation process, and it is vital to clarify the types of load required to create an appropriate analysis process. A design code is a record that sets rules for the design of a new project. It can be used in the design and planning process and monitors other forms of guidance commonly used in the English planning system over decades.

The codes used are the American Concrete Institute (ACI 318-08) Code, the Saudi Building Code (SBC), the International Building Code UBC-1997, and the Minimum Design Loads for Buildings and Other Structures (ASCE_7-10) (SBC, 2018),

In a structural design, the presumed loads are specific international and local design codes for varieties of structures and geographic sites. In addition to the load's magnitude, its distribution, frequency of occurrence, and nature are vital elements of the design. The loads are responsible for deformation and stress in structures, and structural analysis methods evaluate their effects.

Dynamic loads show noteworthy effects, like wind gusts, strong earthquakes, impact loads, and waves. As a complication of the analysis, dynamic loads are usually considered equivalent loads for the normal design of common structures. Design codes generally indicate various load combinations and weighting factors for every load type to ensure a structure's security under various loading circumstances. The load combination equations are modeled according to ACI 318 (ACI, 2019). The SAP2000 model and a 3D model of a three-story building are shown in Figures 11 and 12 below (SAP2000, C. S. I., 2020).

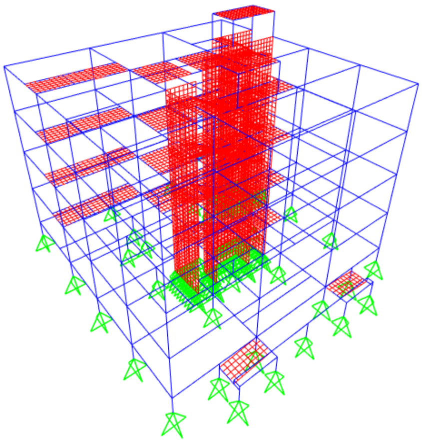


Figure 11: SAP2000 model

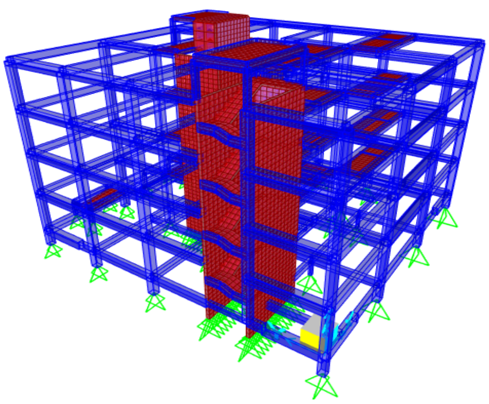


Figure 12: 3D SAP model

## Detailed Time History Analysis Results

The time of oscillation of the building during the seismic interval for the frame of the structure is t=0.648 s, and it is known that the period must be less than this value by using fluid viscous dampers. Applying dampers to the first floor for the dampers will have the maximum effect. It can also be seen that the time was reduced from 0.62 to 0.51 seconds, which is a noticeable difference. However, it is required less than that period to ensure that our structure is stable and safe. The deformed shapes in extruded views for different floors are shown in Figures 13, 14, 15, and 16.

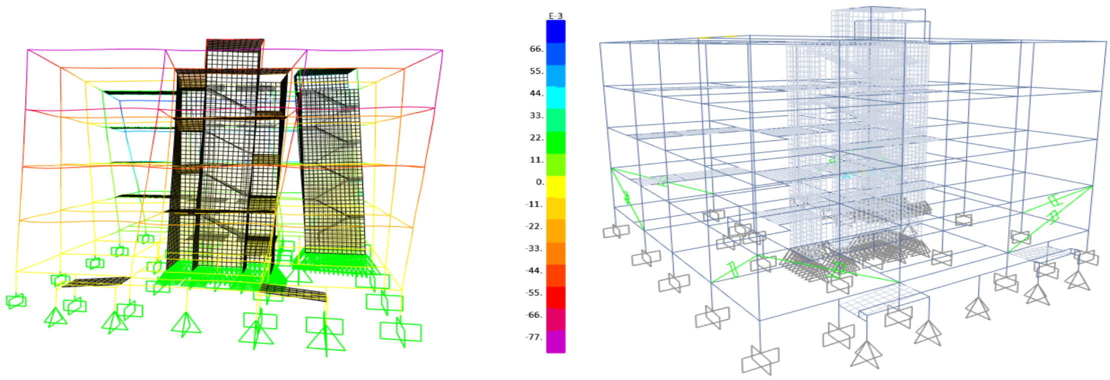



Figure 13: The deformed shape of the structure frame without dampers and with dampers applied to one floor

The image below clarifies the methodology by which fluid viscous dampers are fixed to the structural frame for one story only using SAP2000. FVD has been applied at the corners to maximize the effect of the dampers. In the case in which a damper is installed at the center, the readings were less than the readings obtained by this method (SAP2000, C. S. I., 2020).

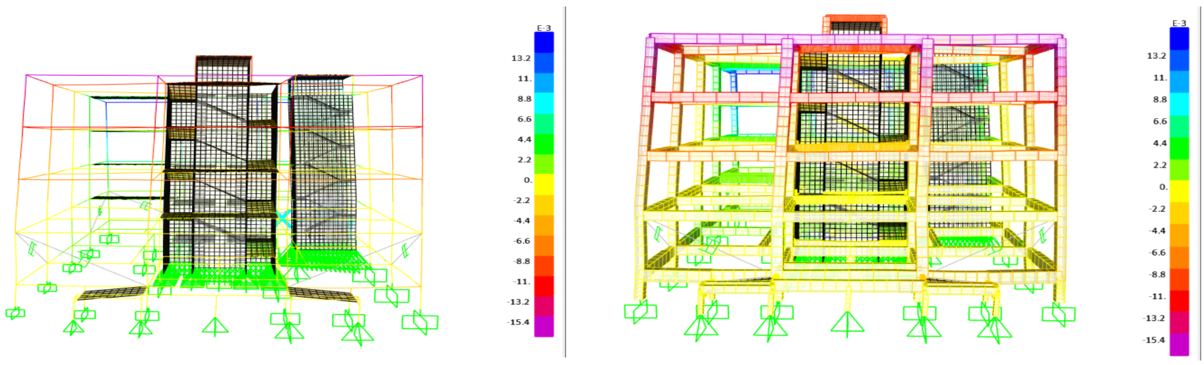



Figure 14: Deformed shape of the structure frame with dampers applied to one floor

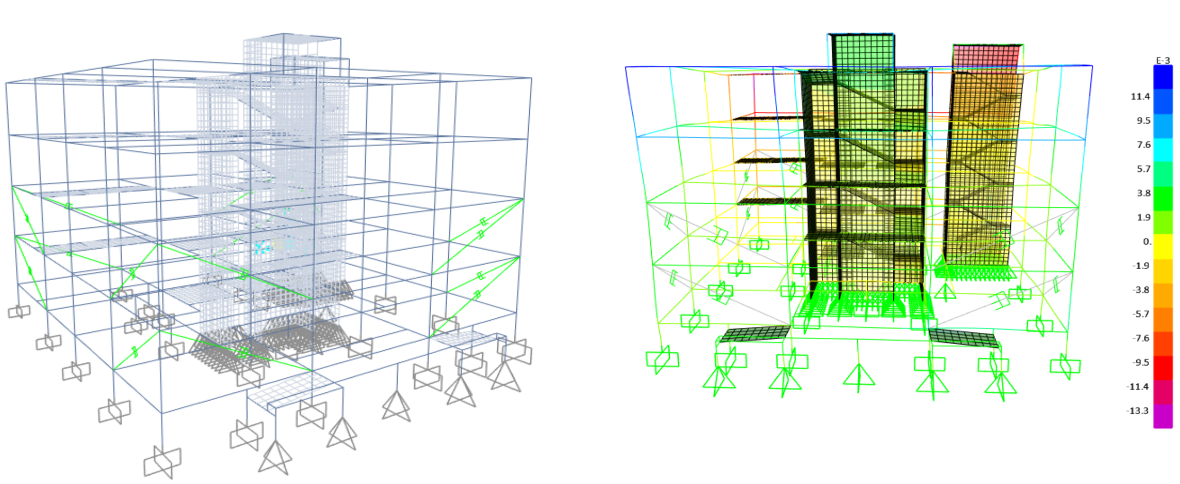



Figure 15: Structure frame with dampers fixed on the first and second floors

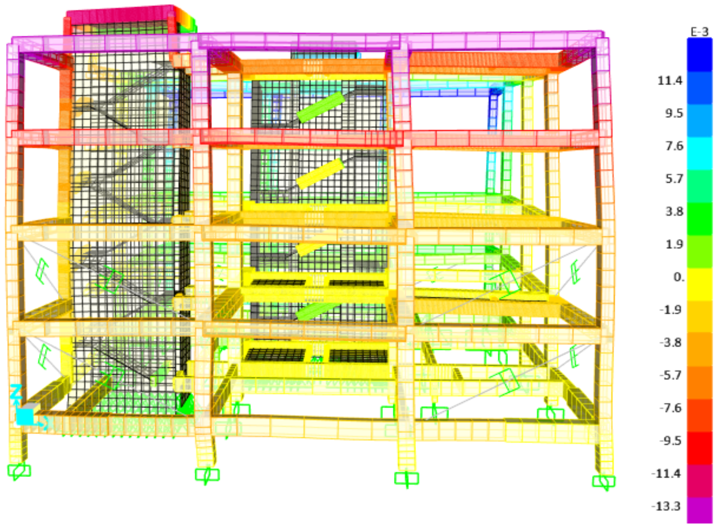



Figure 16: Extruded view and back view with dampers applied to two floors

To conclude, the results for the time history analysis (t) of an earthquake event for different cases are shown in the Table 1

Table 1. Time Period of Building

| MODEL CASE | T(s) |
|---|---|
| Structure without applying any passive control | 0.62 s |
| Structure with FVD applied to one floor only | 0.51 s |
| Structure with FVD applied to the first and second floors | 0.38 s |

The values shown in Table 1 clarify the influential role of using dampers (passive control) in reducing the oscillation time (movement time). Moreover, continuing to add dampers to more stories would reduce the movement time of the structure even more, but that would be a waste of money and effort since the structure is already in the safe range (i.e., from 0.1 to 0.3 or 0.4).

## Dynamic Displacement

In **Case A**, one joint's dynamic displacement is displayed using SAP 2000, but no passive control (damper) is used. The image below clarifies the dynamic movement range of joint 6683; the range for Case A is -22.62 mm to 33.69 mm.

In **Case B** (the dynamic movement of a joint), the same joint is displayed as in the first case using SAP 2000, but in this case, a passive control (damper) is used for just one story of the structure (Figures 17 and 18). The image below clarifies that the dynamic movement range of joint 6683 for Case B is -17.00 mm to 28.19 mm. As it can be seen clearly, dynamic movement was decreased.

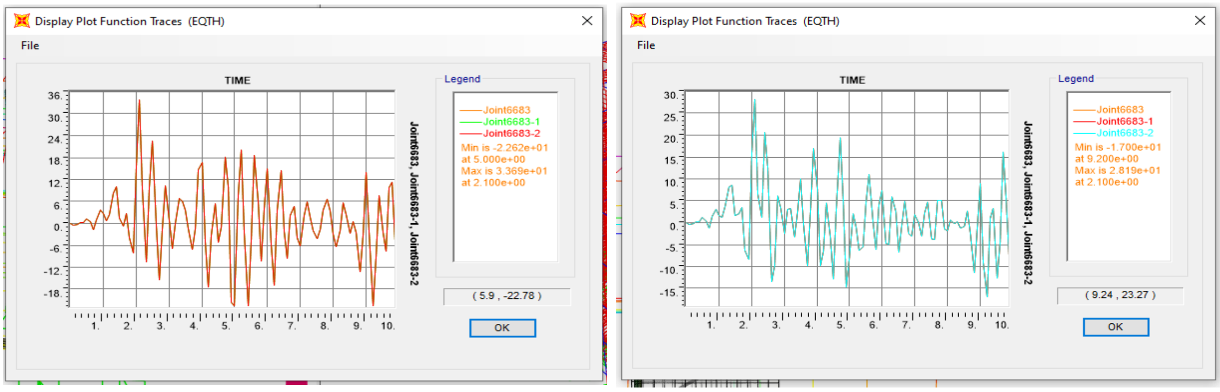


Figure 17: The dynamic movement range of joint 6683 in Case A and Case B

In **Case C**, the dynamic movement of a joint is examined. Initially, the same joint is displayed using SAP 2000, but in this case, a passive control (damper) is used for two stories. The image shown below clarifies that the dynamic movement range of joint 6683 is -8.00 mm to 11.89 mm. As we can see, the dynamic movement decreased noticeably.

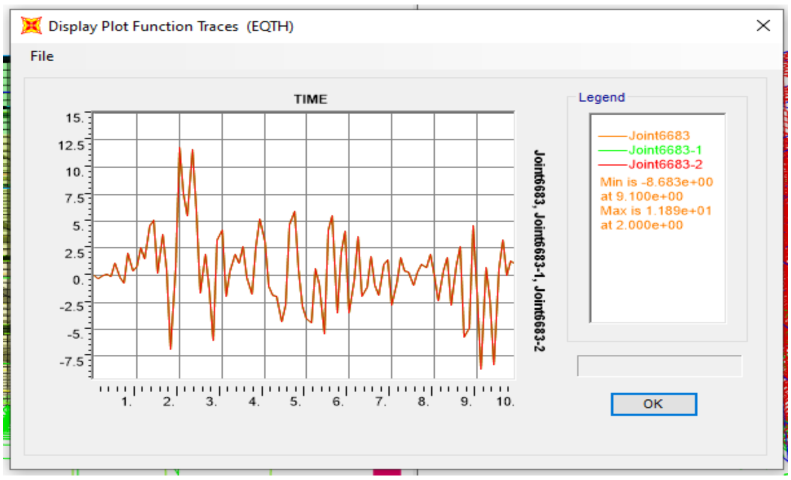


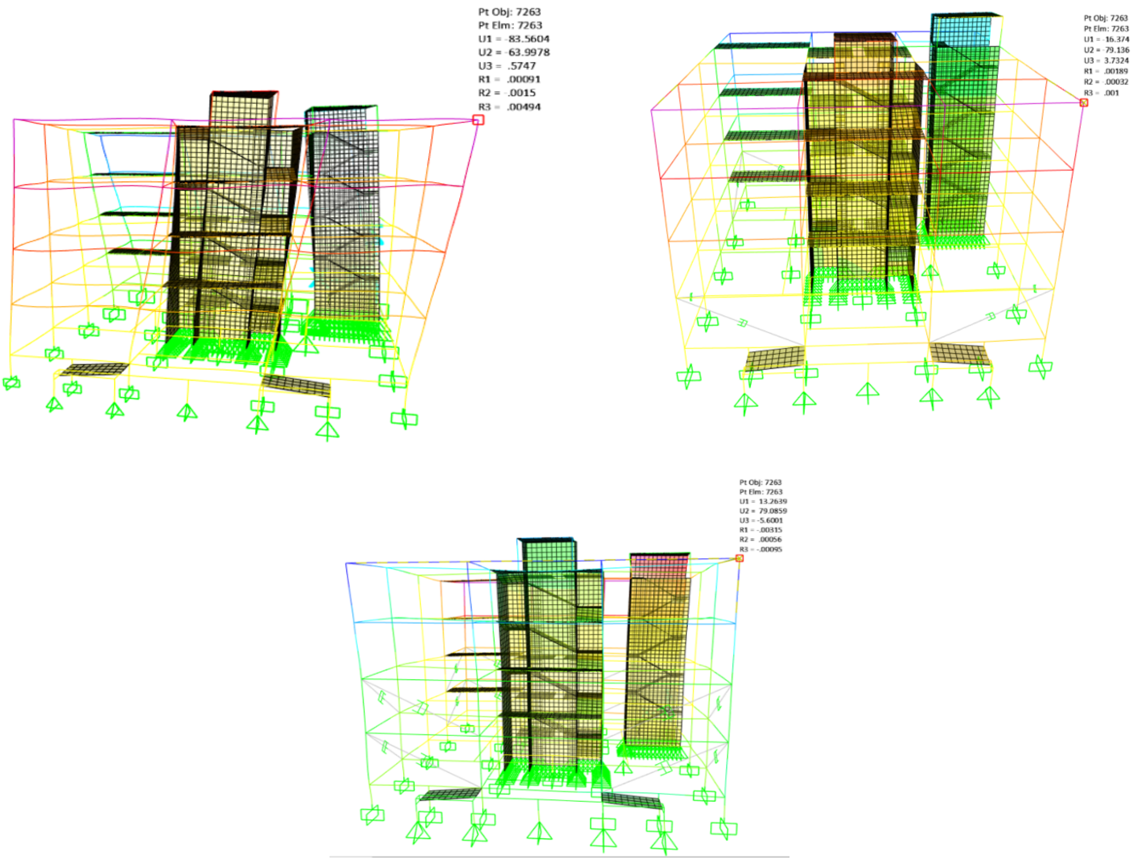

Figure 18: The dynamic movement range of joint 6683 in Case C

In summary, using passive control (dampers) reduces the dynamic movement of the structure, which directly affects the structure's stability and safety. Therefore, the oscillation time and dynamic movement, which are basic factors of the stability and safety of any structure, are affected directly by passive control (in our case, dampers). Since our designed structure is only three stories tall, we can achieve the stability and safety requirements using different concrete sections or other reinforcement conditions. However, reinforcement conditions were applied in these sections to detect changes in the stability and safety of the structure with and without using passive control.

## Static Displacement

For these checks, two joints (6683-1 and 6683-2) are tested for the same three cases that were previously analyzed. In **Case A**, no passive control is used (i.e., no dampers are applied). In **Case B**, passive control is used; specifically, dampers are installed on one floor of the structure. In **Case C**, passive control is used; specifically, dampers are installed on two floors of the structure.

**Case A** **Case B**




**Case C**

Figure 19: Static conditions for the first joint in Case A, Case B, and Case C

When checking the static movement as shown in Figure 19, we consider three axes: U1, which is the movement in the X direction; U2, the movement in the Y direction; and U3, the movement in the Z direction. According to the above image, in Case A, where no passive control is used to support the structure frame, the readings for joints 1 and 2, respectively, are as follows: U1=83.56 mm, U2=63.997 mm, and U3=0.5747 mm; U1=83.56 mm, U2=82.149 mm, and U3=0.97 mm.

In Case B, when dampers are applied to one story only, the readings for joints 1 and 2, respectively, are as follows: U1=16.374 mm, U2= 79.13 mm, and U3=3.73 mm; U1=16.374 mm, U2=49.40 mm, and U3=3.03 mm. There is an obvious difference in the values; most values in Case B are lower than the values in Case A, while some are slightly higher in a way that doesn't affect stability or safety, but eventually, it is a lot better.

In Case C, when dampers are applied to two stories, the readings for joints 1 and 2, respectively, are as follows: U1=13.263 mm, U2=79 mm, and U3=-5.6 mm; U1= 13.26 mm, U2=50.94 mm, and U3=-5.15 mm. These values are similar to or even smaller than those in Case B. This indicates improvements in the structure frame's stability and safety occur when the passive control (dampers) is fixed on the structure to achieve the maximum effect.

After the design process, we determined the following parameters. Beams and column sections for all floors are as follows: Beams 1 and 3 section size = 40 cm x 80 cm; Beams 2 and 4 section size = 60 cm x 80 cm; Beam 5 section size = 80 cm x 90 cm; Beam 6 section size = 30 cm x 60 cm; Beam 7 section size = 50 cm x 80 cm; Column 1 size = 60 cm x 60 cm; Column 2 size = 60 cm x 70 cm; Column 3 size = 60 cm x 80 cm; Column 4 size = 60 cm x 90 cm; Column 5 size = 80 cm x 90 cm (Figure 8).

## Conclusions

This research utilized the most modern models of laser scanners and accompanying software capable of accurately capturing and aligning point clouds. The laser scans precisely captured the current geometry of each structure, which is irregular in many cases due to the inherent complex geometry, aging, corrosion, and structural damage. A four-story building was scanned using a 3D laser scanner to generate architectural and structural drawings. The results showed that the above technique provides the best outcomes for reducing seismic damage collapses. Furthermore, the outcomes can be helpful for future research in this field.

## Acknowledgments and Conflicts of Interest

This research work is financed by the Deanship of Scientific Research at the Islamic University of Madinah. The authors would like to express their appreciation for this support. There are no conflicts of interest or ethical issues involved in this research.

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