INVESTIGATION OF BIM POTENTIALS ON SEISMIC RESILIENCY OF DRYWALL SYSTEMS DURING EARTHQUAKE

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ABSTRACT

INVESTIGATION OF BIM POTENTIALS ON SEISMIC RESILIENCY OF DRYWALL SYSTEMS DURING EARTHQUAKE

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Building Information Modelling (BIM) is a promising technology on resilient design. The use of BIM technology could enable seismic design and installation of non-structural elements. This study discusses the usefulness of BIM in seismic design and assessment of lightweight steel stud gypsum board partition walls (drywall systems). This study also presents the potential of BIM in order to disseminate the information about seismic demands on drywalls in reinforced concrete (RC) structures among stakeholders during the design phase. Thus an integrated and synchronous approach is proposed where the analyst can specify the required precautions or metadata through BIM that eliminates stereotype installations before starting or revising the physical construction process. Two generic office buildings fictitiously located in İstanbul - Turkey, are modeled. One of them is designed according to design earthquake whereas the other satisfies the demands of maximum considered earthquake (earthquakes with 475 and 2475 year return periods, respectively). The required models of these buildings are produced in BIM compatible software and data exchanges are supplied between these environments by Application Programming Interface (API) extensions. The seismic demands on drywalls are presented to show the differences among interior partition walls located in different parts of the building and having various equipment.

The demands on the drywalls are evaluated according to reference data from drywall specification sheets and ASCE/SEI standards. This study showed that, by making use of BIM technology, the relatively vulnerable and overdesigned walls can be easily distinguished and shared with all stakeholders before the installation or renewal of the systems which eventually saves life, time and money throughout life-cycle of the buildings.

Keywords: Building Information Modelling, Non-structural Elements, Seismic Resiliency of the Drywall Systems, Seismic Evaluation of Non-structural Elements

ÖZ

ALÇI LEVHA BÖLME DUVAR SİSTEMLERİNİN SİSMİK TASARIM VE MONTAJ SÜRECİNDE YAPI BİLGİ MODELLEME TEKNOLOJİSİNİN POTANSİYELLERİNİN ARAŞTIRILMASI

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Yapı Bilgi Modelleme teknolojisindeki gelişmeler ve potansiyeller inşaat endüstrisindeki bir çok probleme çözüm olabilir. Yapı Bilgi Modelleme sistemi ile oluşturulacak projeler, tasarım sürecinden itibaren sunduğu detaylı ve gerçek zamanlı bilgi düzeyi ile belirsizliklerin azalmasına, analiz ve tasarım süreci kalitesinin artmasına ve tüm proje paydaşlarının eş zamanlı olarak sürece katılmalarına olanak sağlar. Bu çalışmada, alçı levha bölücü duvarların sismik tasarım ve değerlendirilmesi üzerinden Yapı Bilgi Modelleme teknolojisinin taşıyıcı olmayan tüm bina elemanlarının sismik tasarım ve montajı konusunda etkinliği araştırılmaktadır. Bu sistemdeki entegre ve senkronize edilmiş girdiler sayesinde tek tipleşmiş üretim süreci yerine her elemanın sismik talebi doğrultusunda tasarım ve montaj gereksinimleri belirlenebilir. Böylece yapısal olmayan her bir elemanın sismik tasarım ve montajı için gereken teknik data, tasarım aşamasında tüm disiplinler ile paylaşılabilir. Bu çalışmada, İstanbul-Türkiye'de olduğu kabul edilen iki ofis binası sırasıyla tasarım deprem yer hareketi ve göz önüne alınan en büyük deprem yer hareketi (475 ve 2475 yıl dönüş periyoduna sahip depremler) için tasarlanmış ve bunlara ait bilgisayar modelleri üretilmiştir. Yapı Bilgi Modelleme teknolojisine uyumlu yazılımlar ile üretilen modellerde, programlar arası veri akışı Uygulama Programı Arayüzü metodu ile yürütülmüştür. Oluşturulan bina modelleri için zaman tanım alanında doğrusal dinamik analizleri, seçilen deprem kayıtları altında gerçekleştirilmiştir. Analiz sonuçlarına göre binalarda bulunan alçı levha duvarların, bulundukları konum ve taşıdıkları ekipmanlardan kaynaklanan sebepler ile farklı ivme-kuvvet ve deplasman talepleri elde edilmiştir. Duvarların sismik talepleri, teknik şartnamelerden referans alınan ivme ve katlar arası ötelenme kapasiteleri ile karşılaştırılarak, nispeten zayıf ve/ya abartılı tasarlanan duvarlar kolayca belirlenmiştir. Ayrıca, duvarların aplikasyonunda gereken teknik talepler belirlenip, elde edilen veriler tasarım aşamasında tüm disiplinlerle paylaşılmıştır. Böylece Yapı Bilgi Modelleme teknolojisinden faydalanarak, taşıyıcı olmayan elemanların otomatikleştirilmiş sismik tasarımı inşaat aşamasından önce gerçekleştirilerek, yapıların kullanım süreci boyunca can ve mal güvenliğin sağlanabileceği ve ekonomik kayıpların önüne geçilebileceği gösterilmiştir.

Anahtar Kelimeler: Yapı Bilgi Modelleme, Yapısal Olmayan Elemanların Sismik Davranışları, Alçı Levha Duvarların Sismik Sürdürülebilirliği

To my incredible family…

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LIST OF ABBREVIATIONS

ABBREVIATIONS

ADD	: Addendum
AEC/O	: Architecture-Engineering- Construction and Operation
AIA	: American Institute of Architects
API	: Application Programming Interface
ASCE/SEI	: American Society of Civil Engineers/ Structural Engineering Institute
BIM	: Building Information Modelling
CAD	: Computer Aided Design
CAE	: Computer-Aided Engineering
CSI	: Computer & Structures Inc.
FEMA	: Federal Emergency Management Agency
FF&E	: Furniture, Fixtures & Equipment
FM	: Facility Management
GM	: Ground Motion
IAI	: International Alliance for Interoperability
IFC	: Industry Foundation Classes
IPD	: Integrated Project Delivery
MEP	: Mechanical and Electrical & Plumbing
n-D	: n-Dimensional
PBEE	: Performance-based Earthquake Engineering

PEER	: Pacific Earthquake Engineering Research Center’s
RC	: Reinforced Concrete
SPONSE	: Seismic Performance Of Non-Structural Elements
SSD	: SOFiSTiK Structural Desktop
TEC 2007	: Turkish Earthquake Code 2007
TS 498	: Design Loads for Buildings
TS 500	: Turkish Reinforced Concrete Building Code 2007
VBA	: Visual Basic for Applications

LIST OF SYMBOLS

SYMBOLS

F_p = seismic design force

a_i = maximum acceleration at level i obtained from the modal analysis

a_p = component amplification factor

W_p = component operating weight

R_p = component response modification factor

Ip = component Importance Factor

A_x = the torsional amplification factor

T = period

S = soil type

CHAPTER 1

INTRODUCTION

In this chapter, initially, motivations about the focused problem are presented. Then, based on the motivations, the research questions are defined. It is continued with the aim and objectives of this study. The chapter is concluded with disposition, an overview of the content organization.

1.1. Motivations

In the architecture, engineering, and construction industry, Building Information Modelling (BIM) technology has changed the conventional understanding of project realization. BIM provides an integrated communication environment between all stakeholders. In a shared model for interoperability, information is centrally collected, accessed and updated by all team members. It generates a digital three-dimensional model virtually to elaborate on the problems, analyze and simulate for optimal life-cycle process (NIBS, 2017). BIM opens new horizons on design, construction and maintenance workflow. BIM is not just software including input data in an intelligent model, but also an integrated process throughout project life cycle. BIM's holistic approach enhances collaboration among people, systems, specifications, techniques and business frameworks (Glick and Guggemos, 2009). Developments in BIM technology with the data flow between not only core team but also all team members have enabled planned and productive cooperation, consistent decision making process throughout construction as well as identification of clashes (conflicts) and changes earlier. Furthermore, BIM data includes project management (PM) related subjects such as quantity takeoff, construction scheduling (4-D) and financial consequences (5-D). Subset dimensions of BIM can be extended as as-built operation (6-D), sustainability (7-D) and even safety (8-D) that is nD-enabled multidimensional capacity (Smith, 2014; Bryde *et al*., 2013).

BIM increases predictability of the building's behavior about almost whole life cycle before it is built because building model is created in detailed, well defined and planned with strong coordination so building model includes both physical and analytical data of the whole body. Also, it provides analysis tools for different scenarios and supplies simulation opportunities by making use of digital and integrated data environment. In other words, as Kameedon (2010) states, BIM permits optimization of design with analyses, simulations, and visualization by providing reliable building data. From the design stage of the project, integrated building model consists of detailed information about whole building systems such as architectural, structural, mechanical, electrical, fire supplies, specialist equipment, and building components and furniture. Thus, well-informed project members; architects, structural engineers, system engineers, project managers, clients, general contractors, sub-contractors and suppliers can check the model to reach a desirable performance of building elements and systems. Shortly, as Azhar (2011) states, BIM arises as an advanced way for virtual construction and management of the projects. Future behavior of buildings and their operation has become foreseeable by BIM technology. Adopting BIM accelerates project realization and at the same time, increases construction and operation quality.

With advances in BIM, it is hoped that interoperation and shared working platform will bring new solutions for serious problems in Architecture, Engineering and Construction & Operation (AEC/O) industry such as seismic resiliency of the buildings, safe evacuation of the buildings during the fire, sustainability of the buildings, *etc*. According to Perrone and Filiatrault (2017), one of these controversial, critical, serious and vital issues in the AEC industry is the seismic design and installation of non-structural elements since the recent earthquakes show that a significant number of deaths, injuries and losses are directly related with the vulnerability of buildings' non-structural elements. When it is considered that up to

70% of a building’s value consists of non-structural elements (Figure 1.1a), damage to non-structural elements results with serious loss of life and property even if the buildings survive without any structural failure (Ferner *et al*., 2014). In other words, seismic design is not only structural safety but also the achievement of the safety of the non-structural elements. For this reason, the seismic safety of non-structural elements should be considered in the design stage of the projects. However, the responsible discipline from the seismic behavior of non-structural elements is not clear. As mentioned on FEMA-74 (2011), contractors and their sub-contractors purchase and install all non-structural elements, after construction has been completed. This is not proper for the performance-based earthquake engineering (PBEE) design process because according to performance objectives, a wider group of stakeholders should specify the desired building performance features at the beginning of a project.

In addition to this, according to the report of Wieser *et al*. (2012), in the US, 75% of earthquake losses are comprised of non-structural systems. Non-structural elements also are the reason for over 78% of the total estimated national annualized earthquake loss. Besides, Sullivan and Filiatrault (2014) also mentioned that losses of non-structural elements have exceeded losses from structural damage because of the weak performance of the non-structural elements in past earthquakes.

Non-structural elements account for most of the total investment in typical buildings. Generally, in a commercial building, structural components represent 15-25% of the total construction cost, while the nonstructural components represent for 75-85% of the cost (FEMA E-74, 2012). It is illustrated in Figure 1.1b, in hospital buildings, the non-structural elements compose approximately 92% of the total investments (Perrone & Filiatrault, 2014). Hence, post-earthquake repair or replacement cost of non-structural elements take up a large share of the overall repair cost (Restrepo *et al*., 2011). Put it differently, damage to non-structural components create big economic losses. Also, the failure of the non-structural components negatively impresses the continuity of the buildings function and business. This means interruption of the business causes economic problems.

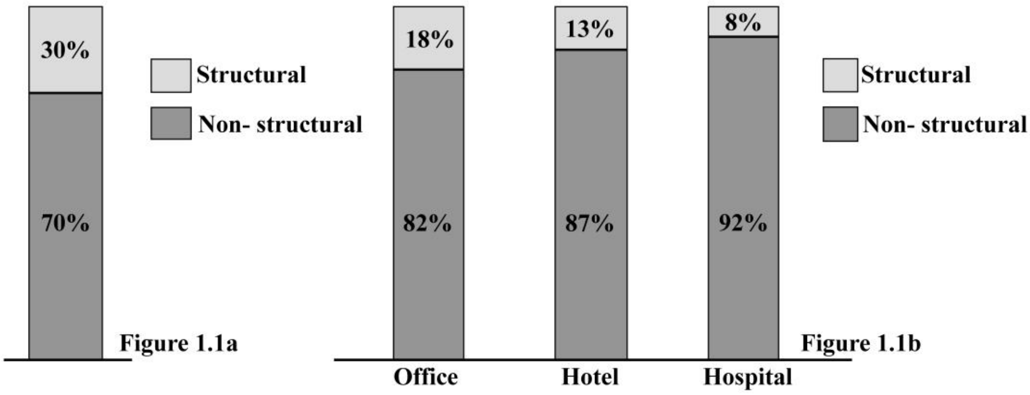

Figure 1.1. (a) Non-structural Elements Compose 70% of Building's Value (Ferner *et al*., 2014); (b) Investment Rate for Typical Buildings Regarding Their Functionality (Perrone & Filiatrault, 2014)

On the other hand, weak seismic performance of the non-structural elements can influence the immediate functionality of the buildings. Especially, after an earthquake, a healthcare center should be in working condition. Like hospitals, schools, offices, airports, *etc*. should remain fully operational. To illustrate, in the 2010 Chile earthquake, four hospitals had to be completely shut down and over ten hospitals had lost 75% of their functionality due to damage to the non-structural components. Therefore, the resiliency of the buildings after earthquakes is a crucial issue.

One of the most important non-structural components is the interior architectural elements (Lee *et al*., 2007). According to Pali *et al*. (2018), lightweight steel partitions are widely used in the building market among the architectural non-structural elements and the considerable damage due to the earthquake is observed to partition walls. During the 1994 Northridge Earthquake, light partitions were tipped over, as shown in Figure 1.2. In 2001, in Seattle- US, during the Nisqually Earthquake, many buildings were suffered from the failure of partition walls (Filiatrault *et al*., 2001).

Figure 1.2. Out-of-plane Failure of Office Drywall Partitions in the 1994 Northridge Earthquake (Reitherman, 2010)

Similarly, in the 2009 L'Aquila earthquake, partition wall failures were one of the most observed cases (Ricci *et al*., 2010). Recently, in many modern strategic buildings like hospitals, airports, defense buildings, schools, the majority of partition walls are produced with most commonly used lightweight gypsum wallboard panels which are called drywall construction system. Although drywalls are lighter than infill panels, it was observed in the 2010-2011 Christchurch earthquake series that serious damage to the drywall was one of the most common failures in the modern buildings (Taslıgedik, 2014). To prevent damage to the drywall, the installation of all interior partition drywalls are overdesigned according to the worst-case scenario but this causes waste of material and workmanship as highlighted by Medeiros & Mello (2016).

Considering the seismic appraisal of drywalls, it is necessary to have detailed and accurate information about the building systems from the beginning of the project to decrease uncertainties and obtain reliable analysis results. With this in mind, BIM could help to enhance certainty and quality of data. In the building model, from the early stage of the project, all building components and connection details are finalized. Required data about any built element can be read diffusively from the model and can be exported to collaborator software and then returning data from external software can be uploaded in the main building model (Welch *et al*., 2014). Perrone and Filiatrault (2017) claimed that Building Information Models could optimize seismic necessities of buildings according to the performance aim of both structural and non-structural elements. All building components in the same model provide an explicit understanding of elements' behavior hence optimization design solutions for seismic assessment could be identified.

Consequently, BIM technology has the potential for opening new frontiers in the building industry. A vital issue in PBEE, seismic requirements and/or precautions of non-structural elements could be developed via exploring BIM tools' opportunities.

1.2. Problem Statement

In the 2001 Nisqually Earthquake in Seattle (US), the 2009 L'Aquila Earthquake in Italy, the 2010 Chile Earthquake in Chile, the 2011 Christchurch Earthquake in New Zealand and the 2012 Emilia Earthquake in Italy, significant damages to non-structural elements were observed. Non-structural components without seismic design threaten life and cause property losses and seismic damage negatively effects the resiliency of the buildings. Though there are codes, specifications, and regulations about the designing and installing process of drywalls, they are not followed specifically (Taslıgedik, 2014). Another issue in the seismic design and installation process of non-structural elements is the lack of certainty in the responsible discipline for the seismic analysis and design of the non-structural elements. The capability of BIM to organize and execute a project could decrease obscurities in terms of responsibilities. The collaboration with BIM achieves the clear definition of role sharing. This increases the feasibility of implementing requirements and regulations about seismic assessment and design.

Non-structural components such as partitions, ceilings, electrical lines, mechanical systems, and sewage systems form 70% of building systems (Ferner *et al*., 2014). The main focused elements of interest are lightweight partitions- drywalls, which are mostly used in buildings such as hospitals, airports, offices, hotels, schools, and defense buildings. In this framework, lightweight partitions, usually interacting with the structural elements, are commonly damaged and induces safety risk, operational disruption and economic losses. The integration of structural and non-structural elements in the same building model can help to reach the optimal seismic performance of the building systems. Also, integrated building model could be beneficial to achieve the target performance level for structural and non-structural elements. The high knowledge level in BIM technology enables early determination and intervention to the critical drywalls in terms of seismic resiliency. As a result, this research discusses whether BIM technology can improve the process of seismic design and installation of non-structural elements or not. Besides, this study investigates how data in building model could be utilized for reducing the seismic risk of non-structural elements.

1.3. Aim and Objectives

The main aim of this study is to demonstrate the effectiveness of using Building Information Modelling Technology in the area of seismic design. By making use of BIM, the seismic design and installation of non-structural elements may be possible. In this framework, for exploring the capabilities of BIM in this area, the seismic design of drywalls as mostly used interior partitions are investigated. The research objectives can be listed as:

- To develop a route for seismic design and installation of non-structural elements by using Building Information Modelling (BIM) technology
- To check the proposed route, BIM process, through case models on the seismic design and installation of drywall
- To explore BIM compatible tools and check their ability in terms of seismic analysis
- To test bi-directional data exchange between different software within the scope of BIM
- To understand the behavior of drywalls during the lateral movement of the buildings and to share critical issues for these components
- To identify possible future approaches to check non-structural elements' seismic performance in the pre-design stage before the construction.

1.4. Disposition

This dissertation contains five chapters. The first chapter is the introduction to the subject. This chapter provides research motivations, determined problem and aim and objectives. The second chapter presents a literature review about BIM technology and it's potentials. The second chapter also includes information about drywalls and possible seismic behavior of drywalls during the earthquake. This chapter continues with investigation of existing studies about the seismic design of non-structural elements by using BIM technology. Finally, it concludes with a critical analysis of the literature.

The third chapter contains the research material and method of the study. First, data exchange methods and their utilities are covered. Then, designed models for case studies, chosen BIM tools and reference seismic parameters are presented. Afterward, case studies for the numerical analyses are explained in detailly. Finally, the proposed flowchart of the study is outlined.

In the fourth chapter, time history analysis results for case studies are illustrated. The results are evaluated in terms of acceleration and inter-story drift ratio values via comparing seismic demand and capacity of drywalls. The results are shared within a BIM environment and so all outputs are available for project stakeholders. Moreover, the validity of used BIM tools and chosen data exchanged method are examined and justified the effectiveness of the proposed methodology. Finally, in the original building model, where output files and analysis results are uploaded in, seismic design force is computed to be a guideline for the seismic design process of drywall elements.

In the last chapter, a summary of the research, main outcomes, limitations of this study and recommendations for further researches are given.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the literature survey is organized under four main sections. The first section gives information about Building Information Modelling (BIM) technology, data flow chain, BIM compatible tools, the analysis options, and BIM's potentials. In the second section, lightweight partitions are introduced, and the advantages of drywalls are covered. Problems with the integration of the structural frame and drywalls are investigated. Seismic behavior and damage types of drywalls as non-structural partitioning members are scrutinized. In the third section, the studies about the seismic behavior of non-structural components and studies on the integration of BIM technology and earthquake safe design of buildings are explored and examined. Finally, Chapter 2 ends with a critical analysis of the literature.

2.1. Building Information Modelling (BIM) Technology

In the Architecture/ Engineering/ Construction (AEC) industry, Building Information Modelling (BIM) technology has been adopted in order to cope with fragmented workflow, insufficient communication and unsuccessful coordination (Campbell, 2007). BIM technology is a relatively novel approach and process that enables positive changes and promising future for the sector to improve overall productivity (Azhar *et al.*, 2012).

The concept of BIM is to virtually construct the building before its physical construction to determine probable difficulties as well as simulate and analyze all possibilities (Smith, 2007). According to the mostly mentioned definition of BIM by National Institute of Building Science (NIBS, 2007), BIM is a shared working platform that digitally represents the physical and functional features of a facility. BIM improves decision-making basis during buildings' life-cycle from conceptual design to demolition. The basis of BIM is providing an information database to all stakeholders of the project to increase collaboration and communication.

The effective execution of BIM needs early participation of all disciplines but conventional project delivery systems restrict the working all discipline collectively. Therefore, a basic premise for working well of BIM is Integrated Project Delivery (IPD) system. That is, the concept of IPD brings all rings of the project chain together like people, systems, business plans and practices in a collaborative process during all stages of the building life-cycle (AIA, 2007).

2.1.1. Integrated Project Delivery (IPD) System

Building Information Model (BIM) is an intelligent, object-oriented and data-rich digital model of the project including all required information. It digitally represents different phases of a facility physically and functionally. The model works as a shared data resource to insert, extract, update and generate information for making logical decisions during the life-cycle of the buildings. The Building Information Model forms an information backbone for interoperability and it is a universal set comprised interconnected files (Smith, 2007). After the building model is completed, BIM, a virtual process, develops construction and operation simulations. Throughout the whole process, BIM brings all stakeholders and systems in a single model from the early stage of the project to provide successful integration, communication and collaboration differently from the traditional process. Improving the idea of communication and collaboration, Integrated Project Delivery (IPD) system arises as a companion to BIM (Azhar *et al*., 2012).

Fragmentation of workflow, lack of communication between professionals, increased project complexity necessitate a new project delivery method in the AEC industry. IPD is a project delivery system that requires integration of all participants collaboratively to take advantage of the abilities and perception of all project members through the entire phase of the project (AIA, 2014). IPD is an effective approach to supply project delivery chain because it brings all key participants such as builders, contractors, subcontractors, designers, owners, estimators, fabricators, all specialists, and owners especially in the early phase of the project together to reduce waste, maximize yield, save time and get ultimate value.

In the AEC industry, the conventional delivery method includes risk and unsatisfactory project outcomes. IPD, as a new project delivery method, tries to solve the problems of industry like time, money, and labor losses. The differences of IPD from traditional (design-build, design-bid-build) delivery methods are listed by Ghassemi and Becerik-Gerber (2011) as follows:

- Collaborative production and process;
- Early participation of all team members;
- Shared jeopardy and award;
- Responsibility among key participants;
- Mutually enhanced project aims;
- A multi-party agreement.

In a sense, IPD is a result of amendments to the traditional project delivery model and it aims to regulate the key participants of the project to eliminate time and money waste, enhance productivity, and reach a win-win result for the related disciplines (Glick & Guggemos 2015). As Anderson (2010) states, the important principals of IPD are mutual respect, reciprocal interest, early goal definition, integrated communication, clearly defined open standards, appropriate technology, and high performance.

Another desirable feature of IPD is co-location of teams that is mentioned by Jones (2014) as 'Big Room'[1] concept. Jones (2014) explains that the ''Big Room'' eases the project process by making all key participants work together in the same room. ''Big Room'' in IPD means supporting collaborative teamwork among multiple disciplines based on BIM technology. Using BIM technology in IPD projects facilitates project decision for a collaborative working environment. As Yang and Wang (2009) present, the most powerful tool for realization of IPD is BIM which works like a catalyst in chemical reaction because BIM, as a virtual model, supplies a working platform during project lifecycle, combines data flow of the whole project process, optimizes of the construction outline via automated virtual construction and fabrication, includes all required information, *i.e.*, the design, construction data, erection guideline and project management in one database. At the same time, IPD provides an integrated environment to get the maximum yield from BIM. For this reason, BIM and IPD should cooperate to obtain the greatest potentials from both. Integrated BIM and IPD process create a new path for unified data flow from multistage to continuous style. Throughout the project delivery process, while BIM acts as an information repository to keep all construction data, IPD assures strong communication between the stakeholders to provide continuous data flow. Additionally, in construction projects, utilizing BIM technology and the IPD system together could produce a project that has an important effect on cost and profit, quality, planning, safety, productivity and constructability (Kelly, 2015).

In summary, in the IPD concept, the main target is the final value. Considering all project operation, the IPD method brings maximum outputs for the clients. From the beginning stage of the project, the integrated working system lets team members know the needs and costs earlier. Thanks to strong collaboration between key partners, the

[1] Big Room
A term derived from the Japanese "obeya." In the Toyota Product Development System, the obeya is a location in which interdisciplinary team members meet to brainstorm and resolve issues on the spot (Jones, 2014).

IPD process can affect cost and function positively by moving decisions to the beginning of the project (Rahim *et al*. 2016). Also, coupling of IPD along with BIM develops project efficiency, reduces mistakes and improves the exploration of variant approaches. In order to importantly improve project output, IPD and BIM are applied jointly and so this could reduce operational and maintenance cost, shorten construction process and increase the project quality (Kelly, 2015).

Consequently, it is understood from Zhang and Guangbin study (2009) that the necessity of cooperation between BIM and IPD is compulsory to drive a novel revolution in the AEC industry. To cope with the lower productivity in the construction sector, advanced tools and technologies should be used. The BIM-based IPD process can enhance the automation level in construction by providing more elements to be produced. In other words, the IPD process accelerates design phases to be ended sooner than the traditional delivery method so for the fabrication and the automated document production, more time is left. Thus, BIM and IPD improve productivity and automation levels. The use of the IPD process, along with BIM are so promising for the AEC industry that brings greater value regarding the level of information and time management as seen in Figure 2.1.

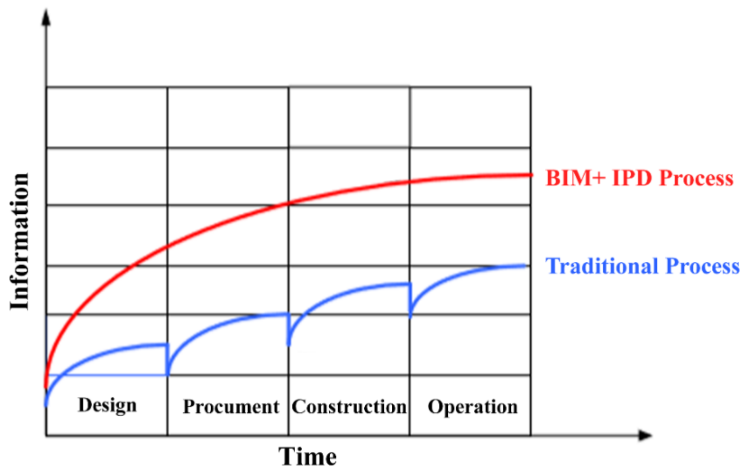

Figure 2.1. Differentiation of Data Flow Paths between Conventional Process & BIM+IPD Process (Adopted from Lancaster *et al*., 2010)

2.1.2. BIM Interoperability for Data Exchange

In every construction project, many parties are included in the process; architects, engineers, clients, contractors and subcontractors, specialists, *etc*. The direct communication between each participant is excessive and it is not necessary for the actual data exchange. Each team member uses a different software so it can be troublesome for the direct transition of models. For the better construction process and maintenance, the issue of interoperability is a matter of collaborative workflows. According to Sacks *et al.* (2018), interoperability is the ability to smoothly share and operating information, which is produced by different vendors, different software among team members. Interoperability has no use for manual copying data. Manual data sharing causes deficiency of data, errors and some level of inconsistency and so it prevents improving automated construction practices. In other words, interoperability is the core of BIM since the data on the building model should be exchanged easily and used efficiently (Santos, 2009).

Arayici *et al.* (2018) emphasized that for the integrated design approach, interoperability is important. In collaboration, interaction and information exchange, interoperability via open standards is critical because the open standards allow the exchange of information regardless of what kind of data produced and which software is used. Also, Laakso and Kiviniemi (2012) presented that interoperability leans on open data standards, enables common file format for the sake of being compatible within all other applications.

Interoperability in BIM technology provides data exchange between different applications and disciplines in a project. There are various ways of sharing and exchanging data depending on the level of interoperability. As mentioned by Rammant (2008), there are a few levels of interoperability. The first level is the basic level which authorizes team members for exportation and importation of data to used software. The manual import/export technique from one software to another necessitates intervention to ensure the coordinates of imported data correctly. In addition to manual exchanging, for all revisions, the import/export process must be redone so for the complex projects, this working procedure fails. Also, each discipline uses different software applications. For these reasons, this level of interoperability turns into inconvenience. Rammant (2008) also introduced the second level of interoperability which is publicly open standard format to allow users to reach all data. In this level, a largely accepted schema is the Industry Foundation Classes (IFC) format in the AEC industry. The most advanced level, according to Rammant (2008), is a direct link between different software. The direct link connects two different application interfaces by using the Application Programming Interface (API).

- **Industry Foundation Classes (IFC)**

The needs of the Architecture, Engineering and Construction & Facility Management (AEC/FM) industry regarding BIM interoperability enable creating and developing the Industry Foundation Classes (IFC) which is a neutral and open standard building data model. The IFC format is developed and maintained by buildingSMART to share data during all lifecycle processes between all stakeholders (Maia *et al*., 2015). IFC has a large background since 1994 when a consortium, called International Alliance for Interoperability (IAI), was started by Autodesk company to suggest integrated application development. Afterward, the name of the international committee, IAI, was changed as buildingSMART to reflect its final aim (Sacks *et al*., 2018).

The Industry Foundation Classes (IFC) was explained by Sacks *et al*., (2018) in their book as an object-oriented data representation schema of the building model to be able to transform data between various applications used by different disciplines. The authors specified that IFC is developed based on ISO-STEP[2], defined in EXPRESS language[3] and designed as an extensible ''framework model.'' As it is pointed out by

[2] ISO-STEP: It is a standard called STandard for the Exchange of Product model data (STEP), developed by the International Standards Organization (ISO) to make interpretable of complex objects for exchange (Sacks et al., 2018).

[3] EXPRESS language: It is one of the main products of ISO-STEP. The EXPRESS language is central mechanism to support the products from different range of industries such as mechanical and electrical systems, process plants, shipbuilding, furniture, finite element models, and others, as well as buildings and bridge (Sacks et al., 2018).

Khemlani (2004), throughout the whole life-cycle phases from conceptual planning to occupation and operation, IFC model addresses not just building components like walls, columns, doors *etc*., but also full domain of building information such as schedule, construction cost, organization *etc*. in the form of entities (data objects) because as mentioned earlier, IFC is an object-based data model which is organized around building entities. Distinctly from the traditional CAD-based geometric data model, information from a data model can be exchanged and used for various analyses, documentation, visualization and calculation purposes. With the help of the IFC data model, Santos, Costa, and Grilo (2017) believe that new studies support semantic interoperability.

According to Laakso and Kiviniemi (2012), the system of architectural IFC data model includes four layers as resource layer, core layer, interoperability layer and domain layer starting from the lowest to the highest. This schema, formed four main layers, is used for describing the geometrical data, the properties of materials and interoperability in BIM model. The resource layer involves commonly used elements in AEC industry and this layer is above the other layers. The categories of entities in the resource layer are defined as generic properties of data objects such as geometry, material, cost, date and time. The resource layer holds a basic definition of these properties of entities in the above layers. The second layer is the core layer which describes entities in the upper layers and comprises two schemas; the kernel and extension. The Kernel supplies the fundamental concepts about elements, relationships, procedures, attributes, and actors. The control extension, product extension, and process extension are defined (Khemlani, 2004). The third layer, the interoperability layer provides a shared platform for the upper domain layer to go smoothly in the exchange mechanism. The final and highest layer of IFC structure is the domain layer specialized for individual AEC domains like architecture, structural engineering, HVAC, construction management and so on (Laakso *et al*., 2012). However, Ma *et al*. (2015) state that the IFC schema always needs development for new attributes to enhance data description and increases the diversity of information in a domain. Sacks *et al*. (2018) affirmed that the final IFC version is IFC4 Add2 released in 2016 as the buildingSMART Final Standard. The latest version of IFC has 776 entities, 413 property sets, and 130 described data types. These numbers show enrichment of IFC schema and this provides working with different systems, extending building information, bridging various applications, and covering different processes including material observation, scheduling, cost estimation, energy analysis, *etc*. For the sake of being compatible, the interfaces of BIM tools and applications have developed according to IFC4 Add2 version. At the same time, new version of IFC schema, IFC5 is in the early planning phase as written in buildingSMART website (2018) in order to complete the gaps in the IFC schema for interoperability because as Ren et al. (2018) presented there are some challenges in interoperability due to observed limitations of IFC version. One of the faced interoperability challenges is missing and untraceable data when the IFC model exported from one software and imported to another. Moreover, the missing information is not detectable so users have to check possible data loss after exchange. The other challenge which is implied by Santos *et al*. (2017) is the lack of entities and property sets. Because of the lack of entities and sub-sets in the domain, data transition in semantic meaning encounters major difficulties. Moreover, as Santos *et al*. (2017) emphasize, IFC schema is tried to include almost all fields of the industry in its domain especially the field of earthquake design. For this reason, the gaps in the IFC schema for the reinforced concrete domain are studied to specify properties and relationships.

- **Application Programming Interface (API)**

Application Programming Interface (API) is one of the file transfer methods in BIM technology. It is also called a direct link or direct native link. The connection between two diverse applications is provided automatically by the link which uses the API. The link works bidirectionally hence it is guaranteed the backflow of data without losses (Fleming, 2016). Sacks *et al*. (2018) notice that direct links based on programming level interfaces are the oldest but still important way for data transition. The interfaces are available for building model in software to create, export, check or delete data.

The interfaces of application supply import and adaption data for receiving another application's data.

Basically, direct links are created between at least different two software programs to exchange data. Therefore, for the compatible interface and supporting export/ import data better, companies compromise between each other. Yousefzadeh *et al.* (2015) defined direct links as extensions (add-ons). Unlike IFC files, these extensions do not work in all software because the links have been built especially for a particular software. Thus, data exchange via direct link is provided in high quality and the final result fulfills more than other file transfer methods. Rammant (2015) made Revit Structure software link to Computer-Aided Engineering (CAE) software by making use of API and showed that the intelligent model is transferred to ETABS, Robot and Scia Engineer without re-entry of required data.

Additionally, for the use of different external applications in BIM platforms, plug-ins are developed. Plug-ins increase the productivity of the design stage, let to perform calculation, run analysis and improve interoperability. Especially, for a reliable solution for simulations, the community of BIM users' needs developing plug-ins. One of the communities comprises of authoring of Autodesk Revit. The community members create plug-ins in Revit API and framework in order to unify design process (Silva, Mussi, Ribeiro & Silva, 2017). That is, when working in cross platforms, to solve the problems and prevent data loss in the exchange process, using bi-directional plug-ins allows interoperability through files. To illustrate, In Revit, CSiXRevit plug-ins provide smooth data exchange between Revit and ETABS/ SAP2000 (Sacks *et al.* 2018).

Summarily, the help of technological developments in the subject of interoperability improves the BIM maturity. This contributes to project optimization, building performances, and sustainability concepts.

- **BIM on Cloud**

BIM data sharing and communication is improved by web-based collaborative working platforms called cloud-base BIM. For the interactive project process which means sharing design, reports, and feedbacks between cross-platforms and cross-devices, a centralized web-based platform can be used for the sake of providing workflow and accessibility to data from any devices (Boeykens, 2015). The success of this live connection method justifies the reachability to BIM Maturity Level 3 which is the last and the most advanced step of BIM technology. A part of the solution to improve collaboration in BIM-based workflows is through online platforms for building model sharing. However, in terms of the coordination flow by using BIM clouds, there are no substantial differences from the traditional method since the coordination is organized by contractors from different disciplines in the virtual platform. This better communication just brings simplification to the process, does not change the process. BIM cloud environments such as Autodesk BIM360 Field, A360, Konstru software provide material and equipment list, quality and safety list, notifications, documentation, tasks schedule, reports but these documentations and information are existing as an individual file in the cloud-based sharing platform (Fernandes, 2013). In other words, the main building model, analysis results and reports are in different file formats so all information cannot be matched automatically in a single model.

2.1.3. BIM Platforms and Analyses

Building Information Modelling (BIM) can be thought of as a pioneer in the AEC and FM industry which offers countless opportunities during the whole lifecycle stage of the project. BIM technology supplies aid to all stakeholders to simulate the building and its environment virtually before construction starts, to determine construction and/or operational problems and to make optimal design decisions. Besides, with the help of BIM technology, n-D models can be created to facilitate communication by simulating all stages of a project (Metkari and Attal, 2013). For all stakeholders who are project owners, designers, constructors, and facility managers, there are lots of BIM applications for visualization, option analysis, sustainability analyses, clash and error detection, quantity survey, cost estimation, site logistics, phasing and 4D scheduling, constructability analysis, building performance analysis, and building management (Azhar *et al*., 2012). Therefore, there is a wide range of BIM software used by different disciplines in the construction sector. Over the years, the software vendors have developed BIM tools for structural analysis, mechanical design, energy and sustainability issues, visualization, *etc*. (Srimathi & Uma, 2017). However, Sacks *et al*. (2018) claimed that the main issue in BIM technology is incorporating analysis software and enabling basic capabilities in the software platforms like getting geometry directly from the model, assigning material properties automatically for the analyses and storing, editing and applying loading conditions. With the correct interface, the produced model represents both the analytical model and analysis input data set.

There are lots of BIM applications in the industry and most BIM platforms contain internal tools for rendering, drawing production and clash detection. Each platform offers distinct interfaces, libraries, and functions for various domains. Among numerous applications, how to select proper BIM tools is explained with four requirements by Latiffi *et al*. (2013); reliable and strong communication, accuracy, usability, the trustworthiness of data exchange.

In object-based BIM platforms, simulations and/or analyses for the physical performance of buildings should be carried out to reach effective production. The commonly used BIM platforms and analysis types and tools are listed in Table 2.1.

Table 2.1. *Commonly Used Platforms and Tools in BIM Process (Adapted from Bouska, 2016 and Fleming, 2016)*

Types of BIM Analysis Tools	**BIM Platforms**
Modeling Tools	Revit ArchiCAD Vectorworks Allplan Tekla Structures SketchUP
Structural Analysis	Revit Structure Robot Structural Analysis Professional Scia Engineer ETABS Tekla Structural Designer RSTAB ProtaBIM
Clash Analysis	Navisworks Tekla BIMSight Solibri Model Checker
Energy Analysis	Revit E-Quest EnergyPlus
Acoustic Analysis	Odeon Ease
Lighting Analysis/ Simulation	Radiance
Construction Scheduling	Navisworks
Quantity Take-offs	Navisworks
Cost Estimating	Navisworks Vico systems CostX
Middleware BIM Tools	Onuma 4projects BIMx BIM+
FM Software	Autodesk Revit Allfa Archibus Archifm.net

Eastman (2011) emphasized that BIM is not just installing and using these mentioned tools and platforms. BIM is not a 3D model or Revit, ArchiCAD, Tekla, which are just platforms. BIM is rather an environment that involves tools, platforms, processes, and relationships.

2.1.4. Benefits of Adopting BIM and Overview

Object-oriented Modelling. BIM technology is an epochal approach that sharply changed the path of the AEC industry development graph in a good way. Unlike Computer-Aided Design (CAD) which represents graphical elements like line, point, *etc*. in drawings, the BIM technology is an object-oriented data model. This means that objects are defined as real building elements and systems like door, wall, room, and columns. These building objects are called smart objects which include all physical and functional features and life-cycle process information. For instance, mechanical equipment, an air handling unit in BIM model includes information regarding its supplier, working principles and clearance requirements. When an object is changed in a building model, an adjacent assembly or object is arranged to continue specified relationship automatically. In other words, when a door, attached to a wall is deleted, the wall is completed automatically (Azhar *et al*., 2012).

Integrated Building Data. BIM technology enables visualization and consolidation of project data starting from the beginning of the design phase as Wang *et al*. (2017) claimed. Utilizing synchronized data and interoperability, BIM facilitates required information for design, calculation, simulation, execution, operation, maintenance, renovation and demolition. Also, BIM procures data for decision-making regarding the project life cycle (Figure 2.2). Hence, the integration of workflow is provided with strong communication and accessibility. That is, the key benefit is to have accessible, editable and sharable building models in an integrated data environment.

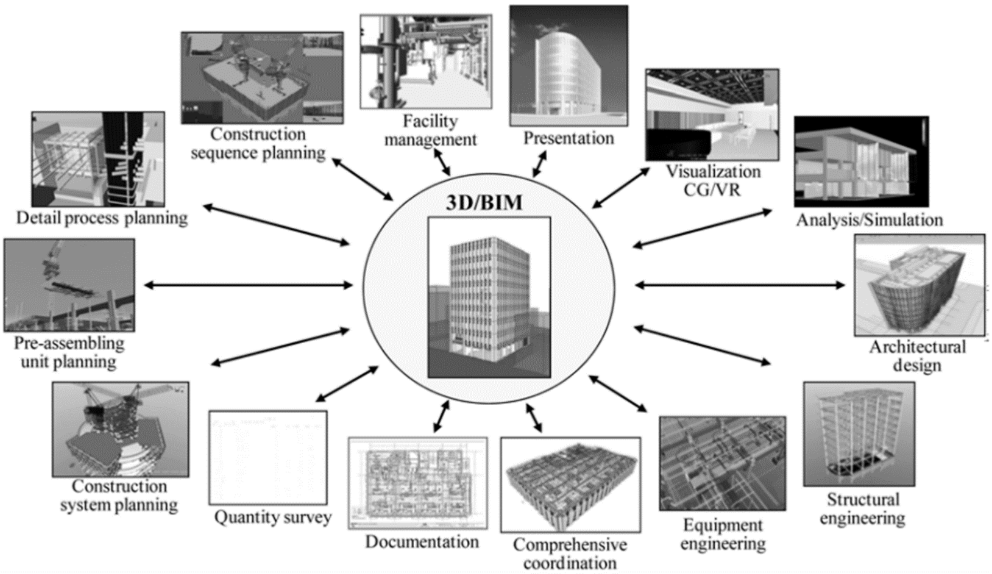

Figure 2.2. Integrated and Intelligent Building Data Model in a Construction Process (Yamazaki *et al*., 2014)

Facilitation of BIM Maturity Levels. BIM comprises of four levels (from level 0 to level 3) of maturity model developed by Mark Bew and Mervyn Richards in 2008 as illustrated in Figure 2.3. Level 0 represents 2D drawings either paper-based or digital. Level 1 is an adaptation process for BIM strategy without interoperability and data exchange. In level 2, BIM process starts, data exchange is provided between different disciplines but a single shared model is not created collaboratively. In level 3, an integrated single model is available for accessing and editing all the time. This level provides a fully collaborative working environment for all disciplines (Nushi *et al*., 2017). In 2013, McGraw Hill Construction reported that in North America, the ratio of professionals who adopts BIM, has dramatically increased from 17% to %71 from 2007 to 2012, which proves that BIM is a trend topic in the AEC industry.

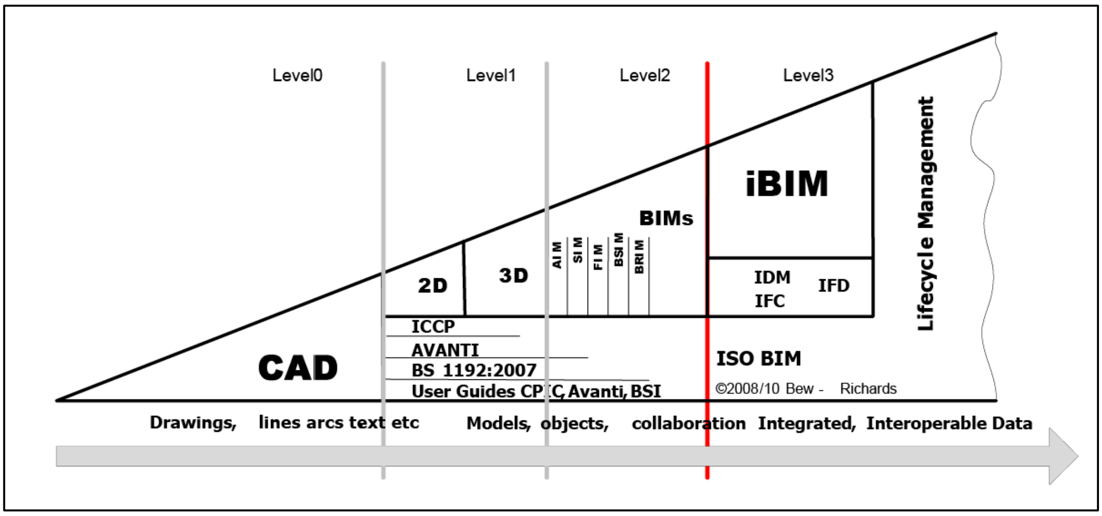

Figure 2.3. BIM Maturity Model in Four Levels (Bew & Richards, 2008)

Multi-Dimensional Building Model for Visualization, Feasibility and Design Benefits. BIM, called n-D modeling, is promising for a new level of project realization mechanism. This multidimensional capacity allows adding limitless dimensions to the building model. 3D BIM (object model) represents all project information and documentation of complex construction conditions in virtual form (Bryde *et al*., 2013). Also, 3D renderings, walkthroughs in the model can be easily generated for visualization purposes. Visualization eases the understanding of how the final product looks like as Metkari and Attar (2013) claimed. The 3D model improves the construction quality since all buildings elements both structural and non-structural are placed in the model and all details are entered from the beginning stage which makes it possible to determine weak points and problems in the early phase of the project. 4D BIM (3D+ time) guides for the timeline of the construction project. In other words, it is used to arrange and simulate the schedule of the workflow (Lattifi *et al*., 2013). Based on scheduling, 4D model is used to monitor the progress in the construction, to increase the understanding of probable issues in the process, to optimize construction sequencing like material order, fabrication, *etc*. and to have better communication of construction scheduling (Srimathi *et al*., 2017). The next n-dimensional model is clarified by Campbell (2007) as 5D BIM, related to cost. By the use of 5D model, quantity takeoff of building materials can be extracted and then the results of the quantity survey can be linked with the cost database. With the 5D simulation, a real-time cost analysis can be performed. In addition to this, 6D, 7D, and 8D BIM show the multidimensional capacity where 6D model refers to operational processes, 7D model is related to sustainability themes and 8D BIM is regarding safety issues. Shortly, the successful implementation of n-D BIM decreases cost, project cycle time and increase quality and sustainability of the projects (Smith, 2014).

Interoperability with Smooth Data Exchange. A centralized model that is created as a single shared building model, stored in the cloud and accessed as well as edited synchronously refers to Open BIM. Open BIM technology enables interoperability between BIM applications. Open BIM gives opportunities to actualize data exchange between multiple different software used by various disciplines using Open BIM technologies like IFC, API file transferring methods. This is a time-saving, cost-effective and well-coordinated way in the construction process. Moreover, with this approach, design problems, errors and omissions can be detected earlier (Sacks *et al*., 2018).

Improving Building Performance by Simulations. Building performance is another important subject in the AEC industry to get optimal production. Building performance simulations can be done by BIM compatible tools for retrieving information from the integrated building model automatically. Various simulation types such as energy performance, environmental performance, indoor air quality, lighting, and acoustics are available in building performance simulations or tools. Using simulation platforms or tools in the early development of design ideas improves the quality of the buildings (Jung, Häkkinen & Rekola, 2018).

Early Intervention to Design Errors. In the construction process, the virtual building model is used for all needed drawings, analyses and documentation. All components of the building and the systems can be added to the building model from the early design phase of the project. Therefore, before starting construction, the design proposal and the building systems can be checked through performance analyses and simulations. If a problem is encountered through analyses, and simulations, the issue can be figured out with innovative solutions in the design phase (Azhar, 2012).

Detection of Conflicts. In the final project model, the project manager merges different files from different disciplines in a just single model. For coordination of different systems, the project manager analyzes the incorporated model which includes all building components and equipment, fixtures, pipes, ducts, conduits, and structural elements and discovers clashes by using BIM clash detection tools. By making use of system coordination before the fabrication and installation of the equipment, around 80% of conflicts can be eliminated (Campbell, 2007). Also, the early realization of clash detection between different disciplines saves cost, reduces errors and yields better service.

Model for Prefabrication. Shop drawings are supplied from the design model so this saves a significant amount of time and prevents errors. Likewise, the building model is transferred to BIM fabrication tools for automated production for enabling faster assembly. Sacks *et al.* (2018) informed about the prefabrication process where the automated fabrication of building components is facilitated by numerical control machines. In the design stage, the location of the fabricated building components is decided and then off-site production is started according to the information taken from building model which reduces the cost and construction time. As Campbell (2007) pointed out the automated prefabrication process is the result of the early participation of subcontractors to the process, integration and coordination of geometry, and accurate information which are all achieved by the help of BIM.

Fertile Workflow. Since BIM process workflow enables unfragmented data exchange, it is different from the traditional paper-based method. Starting from the design stage to the post-construction stage, BIM allows information to spread freely. A smooth workflow path and front-loaded design achieve successful implementation of BIM.

Front-loaded projects show potential problems at the earlier phase of the project where these problems can be solved on time by coordination among the stakeholders. Conversely, in traditional design workflows, the corrections occur during the construction documents phase. Based on Patrick MacLeamy Curve (Smith *et al.*, 2009), Figure 2.4 illustrates the time and effort relationship of CAD and BIM workflows.

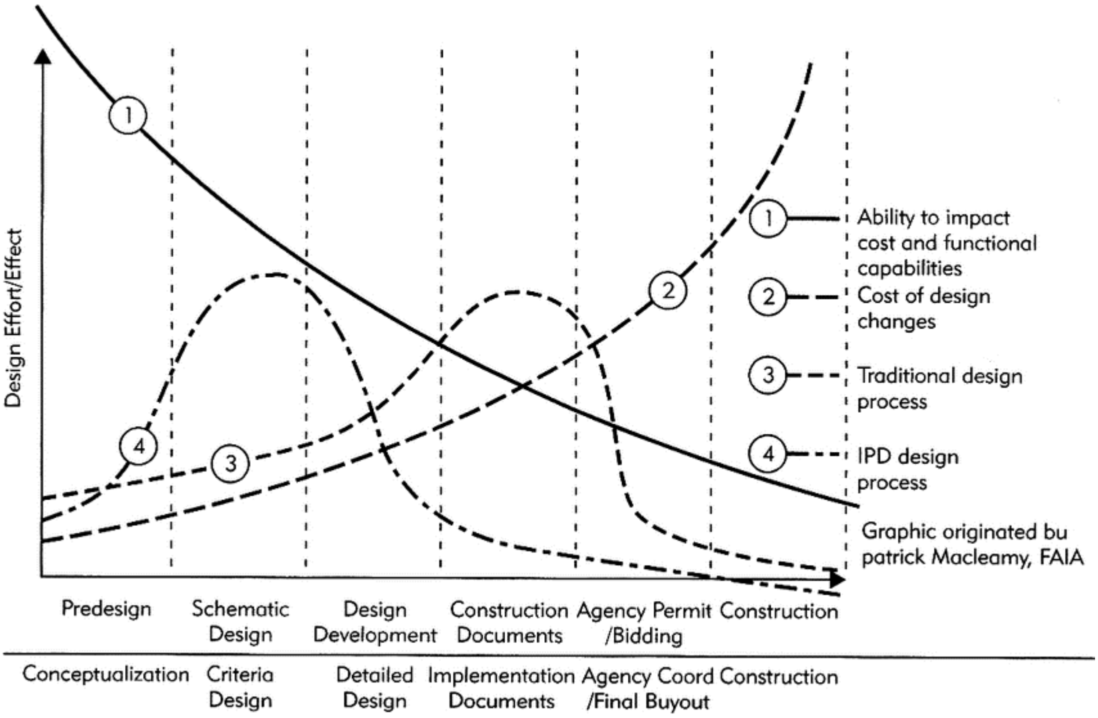

Figure 2.4. Design Effort and the Cost of Change (Smith *et al.*, 2009)

Cost and Time Reduction. BIM provides accurate design decisions for costs and time according to the level of building model's detail. In the project development phase, each team member creates models with detailed information. Azhar (2011) illustrates how developing and using BIM yield both cost and time savings through a hotel project case study. Azhar (2011) showed that the amount of estimated cost saving is over $200,000 which covers approximately 0.43% of the project budget. Considering that BIM cost is 0.2% of the project budget, 0.43% of the total project cost is a considerable amount of cost-saving. Besides, according to the results of Azhar (2011), the scheduled benefit in the whole process is 1,143 hours.

Better Operation and Maintenance. BIM includes information about building systems like equipment, HVAC system, fire system, *etc*. All systems can be checked whether they work well or not during the operation phase by facility managers. BIM-Facility Management (FM) integration provides an interface for sensors and remote operation system (Sacks *et al*.,2018). According to Campbell (2007), the non-graphic information in instructors of equipment and facility operations is related to the geometry in BIM. Thus, BIM works as a central record and special interface to handle, operate and continue facilities.

Adapting BIM technology brings different types of opportunities in the AEC industry. To clarify mostly used areas of BIM, Becerik- Gerber and Rice (2010) surveyed in the construction sector. The target group of the survey was construction managers, contractors, and subcontractors where the number of applicants was 424. The results of the study illustrate that the ‘‘top three’’ tasks of BIM usage are visualization (63.8%), clash detection (60.7%) and building design (60.4%). As-built model, building assembly, construction sequencing, program/massing studies, model-based estimating, feasibility studies, alternative development, direct fabrication, environmental analysis, code review, facilities management, LEED certification, and forensic analysis were the following tasks in order. Survey results clearly illustrate that BIM is not just a 3D model like supposed in primitive minds. According to Becerik- Gerber and Rice (2010), the usage of BIM is limited, and the grand potential of BIM has not been reached yet. Similarly, Sacks *et al*. (2018) indicated that the ‘‘BIM revolution’’ is still on-going progress. The expected developments in BIM can be listed as: fully digital design and construction, wide off-site prefabrication, the advance of innovation in construction, artificial intelligence application, support to sustainable construction and improvement in automated code-compliance checking (Sacks *et al*., 2018). Shortly, BIM plays a critical role in the AEC industry and moreover, with the key changes in BIM, the construction industry evolves into the digital industry progressively.

2.2. One of the Mostly Used Non-structural Elements: Drywalls

Buildings' systems consist of structural and non-structural elements. While the structural elements are the main load bearing part of the buildings, the non-structural elements are all the systems and components connected to the floors, walls and structural system of the buildings (Perrone & Filiatrault, 2017). Non-structural elements are also called as building attachments, architectural, mechanical and electrical elements, secondary elements and secondary structural elements (Villaverde, 1997).

Non-structural elements are classified into three major groups by FEMA E-74 (2012): 1) Architectural Components, 2) Mechanical and Electrical & Plumbing (MEP) Components and 3) Furniture, Fixtures & Equipment (FF&E) and Contents.

Looking from the closer perspective to architectural components, they are divided into two groups as exterior construction and interior construction by Miranda and Taghavi (2003). The exterior construction system includes walls, doors, windows, and glazed walls and parapet components while the interior construction system includes partitions, doors, wall finishes, and ceilings. The mostly used architectural component in living spaces is partitions. The partitions separate the building into the areas, and form architectural living spaces (Lesnıak *et al.*, 2014).

According to Condeixa *et al.* (2015), for interior wall construction, masonry units wall which is a conventional internal wall system, and drywall system, which is the new way to modern technology, can be used. Usually, the new suitable alternative, drywalls are preferred for the interior partition walls. Taşlıgedik (2014) stated that the most commonly used partition wall systems in the world are drywalls. In New Zealand, the United States and European countries, and also in developed countries, drywall type interiors are very popular. Especially, as Howale & Gupta (2013) remarked, in India's healthcare centers, with the adoption of drywall systems, a transformation of building partition systems is observed. In residential type buildings, hotels, hospitals, schools, theatres, and industrial buildings, drywalls are used for interior partitions as the preference of the construction.

Drywall partition is also called gypsum wallboard panel (Kanvinde *et al*., 2006), plasterboard partition (Magliulo *et al*., 2014), light partition (FEMA 74, 2011) and lightweight partition system (Knauf, 2018). Drywall systems are constructed with light-gauge steel frame or timber frame which are covered by gypsum boards (Lee *et al*., 2007). Tasligedik, Pampanin, and Palermo (2015) claimed that the two types of drywall systems are used currently in the buildings; light gauge steel-framed drywalls and timber-framed drywalls. Two types of applications are constructed in the same way except for framing material. Among the two types of drywalls, steel-framed is the most preferable type because of the simple installation. According to Restrepo and Bersofsky (2011), in many parts of the world, the light gauge steel frame is chosen in commercial and hospital buildings.

2.2.1. Drywall Systems, Industrial Approaches, and Standardizations

Drywalls are very popular partition types in the world currently (Tasligedik, 2014). Drywall partitions are used to create different spaces, to isolate the spaces from fire and noise and to provide heating-ventilating-air-conditioning needs (Davies *et al*., 2011). These drywall systems consist of light framing covered by gypsum board, joint connection and attachments like a screw, joint tapes, insulation (Figure 2.5). The substructure of the non-load bearing drywall partitions, which are bounded rigid structural frame or upper and lower floors, is made of metal studs and wood studs (Knauf, 2018). According to Davies *et al*. (2011), the most preferred choice is steel framing in commercial buildings due to the low weight of the steel framing compared to the wood framing and variance in the moisture level of the wood framing members. Also, owing to the non-combustible characteristics of steel, steel framing is used as substructure materials of the drywall systems in many commercial buildings. It is remarked by Tasligedik *et al*. (2015) remarked because of the easy installation of the steel stud frame. Besides, as Restrepo and Bersofsky (2011), Restrepo and Lang (2011) stated light gauge steel frame is used for commercial and hospital buildings around the world. As a result, mostly preferred light gauge steel stud drywalls are interested in this study.

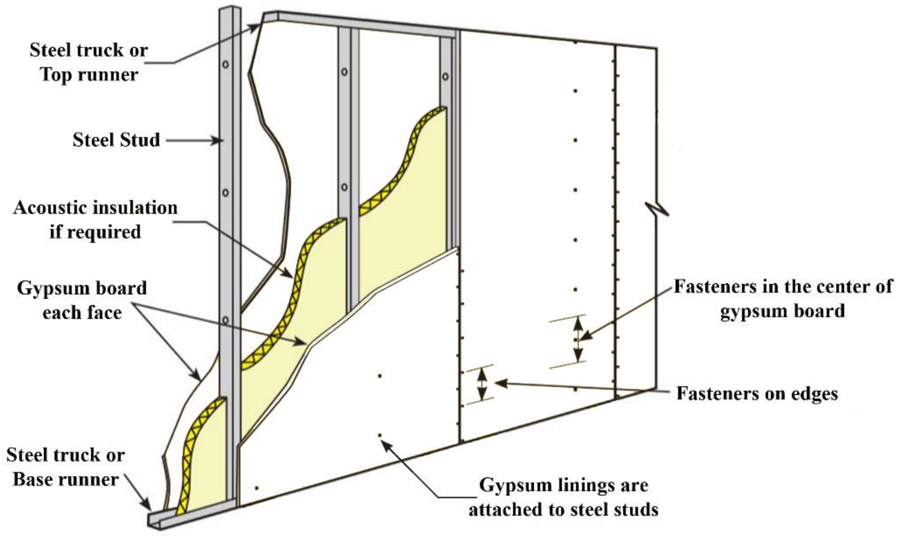

Figure 2.5. The elements of a light-gauge steel-frame gypsum board partition walls (Adopted from Building & Construction Authority Publication)

- **Installation of Drywall Partitions**

In contrast to traditional construction methods of masonry infills, the installation method of drywall systems is easy, fast and efficient. The productivity of drywall systems is approximately four times better than heavy partitions in terms of man-day (Building and Construction Authority, 2008). The installation procedure of light-gauge steel stud framing drywalls is explained by Lee *et al*. (2007). First of all, the base channels are bolted to bounding elements like beams or floors and then runners (steel trucks) are bolted to top beam/floor and bottom floor. Afterward, metal studs are placed and bolted to columns or walls and attached to the runners to create subframe vertically. The spaces between studs are stated using generally 600 mm. According to Knauf (2014) documentation, for thermal and sound insulation, mineral wool boards are installed between studs if it is needed. Then, the next step stated by Lee *et al*. (2007) as covering the substructure with gypsum boards by screwing to studs. The writers specified that gypsum boards are located on the studs horizontally. If it is required, the second or third layer of gypsum board is glued on the first layer. The direction of the boards should be opposite to the former board. Finally, the joints between the top layer gypsum boards are sealed. In the installation process, in order not to face with undetermined information, gypsum board thickness and number of layers, stud spaces, and installation procedures should be decided in the early design stage according to practices as writers mentioned. The behavior of drywalls changes by altering the specifications of each component in the system. Thus, the specific approaches and applications for each components of drywalls are necessary (Henkel *et al*., 2008). The main components of drywalls are profile types of the substructure and gypsum boards.

Boards. Different types of gypsum wallboards, claddings or linings, made of different materials, are produced according to different standards and requirements (regulated in DIN18180) such as fire-rated, water-resistant, acoustically enhanced, impact-resistant and mold resistant. The sizes of gypsum board panels are standardized; 1200 mm in width and 2500 mm in height but custom sizes are produced for bulk order. Their thickness varies from ¼ inch (6.3 mm) to 1 inch (25.4 mm). It is required by most building codes to use ½ inch (12.7 mm) or 5/8 inch (15.9 mm) gypsum board panels for drywalls in single-thickness applications. The weight of the boards differs in terms of technical specifications. The unit weight can be exemplified such as 8, 9, 11, 14.5, 15.5 kg/m2 (Design and Construction Guidelines and Standards, 2008).

Profiles. The subframe of drywalls includes metal profiles for top and bottom runners and studs. The width of the profiles is various from 50 to 150 mm. The using width of the profiles is effected by sound insulation demand, needed load bearing capacity of the wall and required height of the wall. For the framing elements, generally, C and U profiles are used. C studs are placed inside U runners in 60 cm spacing as recommended by Knauf. The spacing can decrease to 30 cm or 40 cm or increase to 90 cm according to the needed stability and height of the wall. Profile type, stud spacing, and anchoring distances change according to wall height, wall condition and earthquake zones (Henkel *et al*., 2008).

2.2.2. Transition to Drywalls and Acquirements

Recently, the construction industry has gone into overdrive so the requirements and desired standards for building materials and systems have changed. For the wall construction systems, masonry unit partitions (*i.e*. clay brick wall and concrete block wall) were used in the buildings but the performance of the infill systems influenced negatively the performance of buildings due to missing quality control. With the improvements in the construction industry in the developed regions, gypsum drywall systems replace by masonry infill walls as a better alternative. Thanks to the properties of gypsum material, it has been used over the years in the construction industry. In the wall system, gypsum is used as a plasterboard. It is prefabricated building material and it encourages the construction sector for growth in most countries (Howale and Gupta, 2013). The advantages of drywalls are specified by comparing with heavy wall systems in the following sub-titles.

Dry Construction. As the name states, the production of drywall systems is the water-free process that is all used materials are dry except filling compound. According to Gyproc Saint-Gobain official website, when drywalls are compared to masonry infills, drywalls use 95% less water and so drywalls are produced four times faster than masonry infills. The system does not contain water so it is not necessary to wait for curing and drying time thus the construction process speeds.

Speed of Installation. Thanks to enhanced prefabrication of drywall system and their equipment, gypsum drywalls are easily installed and it does not need more labor force. Also, the drywall systems let service management like electrical works. Different from masonry infills, service activities are planned so needed slots are ready before the installation process hence this makes the process fast (Gyproc Saint-Gobain, 2018). It provides five to eight times faster construction as Howale and Gupta (2013) mentioned.

Lightweight. Lighter drywall systems reduce the overall load of the structure. Gyproc Saint-Gobain (2018) claimed that drywalls provide structural cost savings of approximately 15%. Comparison table of dead weight per unit area of masonry and drywall partitions presents weight reduction clearly in Table 2.2.

Table 2.2. *Dead Weight Reduction Using Drywalls Instead of Masonry Partitions*

(Adopted from Henkel et al., 2008)

1 m^2 Internal wall as	Weight per unit area
• **Masonry (**d=11.5 cm)	Approx. **145 kg/m^2**
• **Metal Stud Partition**	
Single-layer cladding	Approx. **25 kg/m^2**
Double-layer cladding	Approx. **50 kg/m^2**
Weight Reduction by <u>65% to 83%</u>	

Flexibility. Drywalls can be installed and demolished simply and speedily so floor plans can be changed to regenerate the areas. In other words, drywalls lead to create and divide the spaces and it provides flexible interior design (Henkel, Holl, & Schalk, 2008).

Sound Insulation. Good sound insulation provides acoustical comfort in the living spaces. Drywalls work on mass-spring-mass principle so it provides sound insulation levels of 70db+. The capable of sound insulation performance of drywalls is raised by inserting of rockwools between gypsum boards. In masonry walls, acoustical comfort can be provided with extra layers by increasing the thickness of the wall (Gyproc Saint-Gobain, 2018).

Fire Protection. Gypsum based drywalls resist fire up to four hours to sustain durability, insulation, and integrity. In four hours, eviction is provided until a fire erupts. For the excellent fire resistance features, the ingredients of the gypsum boards like crystalline water and calcium sulfate play an important role (Howale *et al*., 2013).

Thermal Comfort. The thermal insulation of drywalls is 5 times better than masonry infills due to the low thermal conductivity of gypsum and so this reduces the energy consumption of buildings (Howale *et al*., 2013). Besides, the crystalline form of gypsum absorbs the excess moisture from the air. Vice versa when space is dry, gypsum boards eject the moisture to the air again. That is, it provides balanced air humidity (Henkel *et al*., 2008).

Aesthetic Appeal. Drywalls allow continuous surfaces and simplicity in decoration. Drywalls provide wide opportunities in terms of shapes and sizes. As a final product, a smooth, crack-free undulated-free wall can be produced (Gyproc Saint-Gobain, 2018).

Environmental Friendly. The raw material of the drywalls is gypsum. Gypsum is supplied from natural reserves in other words gypsum is 100% recyclable and environmentally friendly material. When drywalls are compared with conventional partitions like the brick wall in terms of sustainability, for the production of infills, brick, soil, water, coal, and biomass require. The usage of these raw materials damages to the environment causes air pollution, increases the amount of greenhouse gas. Unlike infills, drywalls, environmentally friendly products, save natural resources (Howale and Gupta, 2013).

Less Transportation. Drywalls are light materials and dry systems so these systems are convenient to transport. However, for the transportation of brick or sand, *etc*. for infills, owing to large volumes of materials, the high cost is involved. Henkel *et al*. (2008) illustrated the differentiation of spending transportation force between drywall and masonry infills. It is produced 100 m^2 masonry works with a lorry load of lime sandstone while 800 m^2 drywall with single sheeting or 400 m^2 drywall area of double cladding is created with the same load of gypsum board.

Simple Reconstruction/ Repair. Drywalls can be repaired easily and quickly with less effort, less labor force and so building can resilience it's function. Resiliency is important for both economic and infrastructure in hospitals, schools, airports, *etc*. That is, drywall damages minimize service disruption in the buildings. Conversely, damage to masonry infills needs different raw materials, more skillful craftsmen and serious cost and time (Henkel *et al*., 2008).

Offering Benefits in the Area of Earthquake Resistance. Drywall systems have a positive impact on seismic behavior thanks to the less weight of the components. Depending on the mass, imposed upon and transferred force on partitions is fewer and also, the dead load of the system is less than solid construction. Therefore, this decreases the hazard severity during earthquakes. In Henkel, Holl and Schalk's exemplary study (2007), it was shown the effect of seismic influences in two different partition systems; masonry infill and drywalling infill. The results revealed the various earthquake loads on the masonry infills and drywalls. While the numerical value of earthquake loads on non-bracing masonry infills is 1459 kN, the earthquake load on drywalls is 1109 kN. That is, the earthquake load on non-bracing masonry infills is 1,32 times more than the load on drywalls. If the earthquake load on drywalls is compared to loads on bracing infilling, the load value on bracing infill increases to 2919 kN. Hence, this time, the earthquake load on bracing infill is 2,63 times more than the earthquake load on drywalls (Henkel *et al*., 2007). Although this benefit of drywalls, during the earthquakes, drywalls are still one of the most damageable components in the buildings (Taslıgedik *et al*., 2015) so resiliency of drywalls is important after the earthquakes.

The distinctness of the drywall systems and solid infill units are clarified. The comparison results reveal that partitions with modern material and system have many advantages in the mentioned principles above. Therefore, it is understood why the construction industry prefers drywall systems rather than masonry infills. Recently, the use of gypsum wallboards is going up especially in Eastern and Western Europe as Petrone *et al*. (2016). Therefore, the serviceability/usability and operability of drywall systems after an earthquake is of capital importance.

2.2.3. Reasons and Results of Damage to Drywalls During Earthquake

The seismic behavior of partitions is a critical issue in the scope of Performance-Based Earthquake Engineering (PBEE) (Petrone *et al*., 2016) because damages to partitions may cause falling hazards, obstruct passages and jeopardize people to exit from buildings. Some equipment like electrical panels, shelves or heavy items, *etc*. are anchored to lightweight partitions so the failure of wall elements automatically damages to other components in the buildings. Therefore, the seismic damage reasons for drywalls should be detected. Then, the partitions should be properly designed and installed (FEMA 74, 2011).

Non-structural elements generally are classified into two groups in terms of behaviors during the earthquake; acceleration sensitive (force-sensitive; Kumar *et al*., 2017) or displacement sensitive (drift sensitive; Wieser *et al*., 2012). Acceleration sensitive components such as piping systems and cable trays etc. subjects to damages like overturning or excessive sliding caused by inertial forces and accelerations in the structure. Whereas displacement sensitive non-structural components suffer from excessive distortions caused by inter-story drifts owing to attachments to the structural frame (Filiatrault, Perrone, Merino & Calvi, 2018). When the buildings are exposed to the horizontal load during the earthquake, structural elements can deform, bend, stretch or compress as a response. The lateral deformation of the buildings on each floor, called as story drift, differs from between adjacent floors. Because of this various deformation of the structural members, rigidly attached non-structural components to the structural frame have to distort and displace but brittle materials cannot stand for and then they fail (FEMA-74, 2011). In this section, lightweight partitions' behaviors are investigated during the earthquake in the scope of this dissertation study.

Drywall partitions are the most popular interior lightweight partition walls for all types of building in New Zealand (Dhakal *et al.*, 2016) and also in U.S.A. and Japan, drywalls are the most commonly used interior partition wall types (Lee *et al.*, 2007). In the buildings, drywall systems are attached to bordering structural frame or upper and lower slabs. Owing to these attachments, wall systems are prone to damage induced by seismic activity (Tasligedik *et al.*, 2015). The damages to drywalls caused by seismic movements are observed in any type of buildings very often. According to the FEMA-74 (2011), survey results showed that out of 50 damaged high-rise buildings after a moderate earthquake, it is observed damaged to drywalls in 43 of the 50 buildings. Tasligedik, Pampanin, and Palermo (2015) presented that in the 2010-2011 Christchurch Earthquake sequences, moderate and extensive damages to drywalls are observed commonly in many modern buildings and they needed to repair or regenerate.

The seismic performance of the drywalls has been investigated for years by many researchers such as Freeman (1971); Adham *et al*. (1990); Lee *et al*. (2007); Filiatrault (2010); Restrepo and Bersofsky (2011) *etc*. However, Dhakal *et al.* (2016) stated, drywalls are tested without the inclusion of the surrounding elements in most of the seismic studies. In the real case, drywalls interact with the structural frame or top and bottom slabs. Getting results from seismic testing without a bounded frame does not represent the actual response since the bounded frame makes the drywalls more vulnerable due to inter-story drift or displacement. In other words, lightweight partitions are brittle materials, therefore, they cannot tolerate significant deformations of the structural members and so they crack due to pushing directly of structure. Moreover, according to ASCE/SEI 41-13 (2013), light partitions and their connections should resist both in-plane and out-of-plane forces because partitions are considered drift sensitive in their planes (Figure 2.6) and acceleration sensitive in the out-of-plane direction (Figure 2.7). Therefore, for the stability check of the components, out-of-plane forces are considered and for the strength of the components, in-plane loadings are taken into consideration.

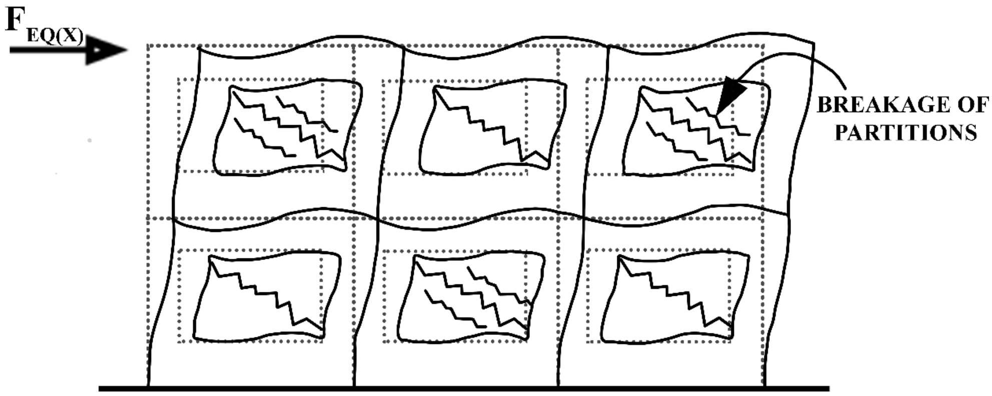

Figure 2.6. Deformation based failure in the in-plane loading (Adapted from FEMA 74, 1994)

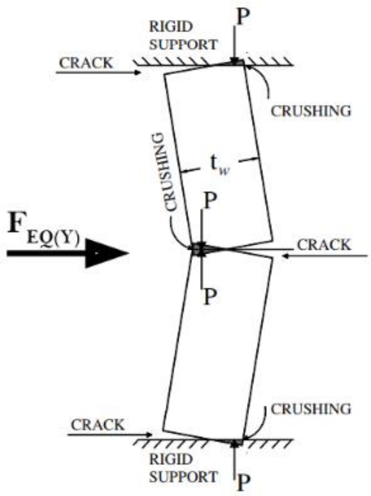

Figure 2.7. Forced based failure in the out-of-plane loading (Adapted from Abou-Zeid *et al*., 2011)

In-plane or out-of-plane forces on lightweight partitions may cause losses if the loading exceeds the certain damage threshold. Due to the deformation and force-based actions in the flexible structures, damages are observed in the brittle full-height partitions. Typical events include cracked wall openings, corners, and vertical joints, spalled finishes, crushed and deformed panels and joints, detached partitions, failed connections and plastic deformation of the studs. The response of walls against in-plane loading is shear cracking, frame distortion and separating of surface finish. In loaded out-of-plane condition, walls can suffer from flexural cracking, shear in joints among wall-structure and collapse (FEMA 356, 2000; McMullin *et al.*, 2007; FEMA E-74, 2011 & Pali *et al*., 2018).

Figure 2.8. In-plane damage owing to building deformation (Fiorino *et al*., 2015)

Figure 2.9. Out-of-plane damage owing to inertial forces (Reitherman, 2010)

In the scientific studies about the seismic performance of interior drywall partitions, many experimental investigations are carried on to observe the seismic response of these components. The experimental tests of Pali *et al.* (2018), Dhakal *et al.* (2016), Lee *et al.* (2007), Petrone *et al.* (2016), Tasligedik *et al.* (2015), Fiorino *et al.* (2018) and Magliulo *et al.* (2014) exhibit the wall damages under in-plane and/or out-of-plane quasi-static cyclic loading conditions. As an example of the test set-up, procedure and results, the study of Lee *et al.* (2007) is explained and reported. The schematic depiction, various details of the test specimen is shown in Figure 2.10.

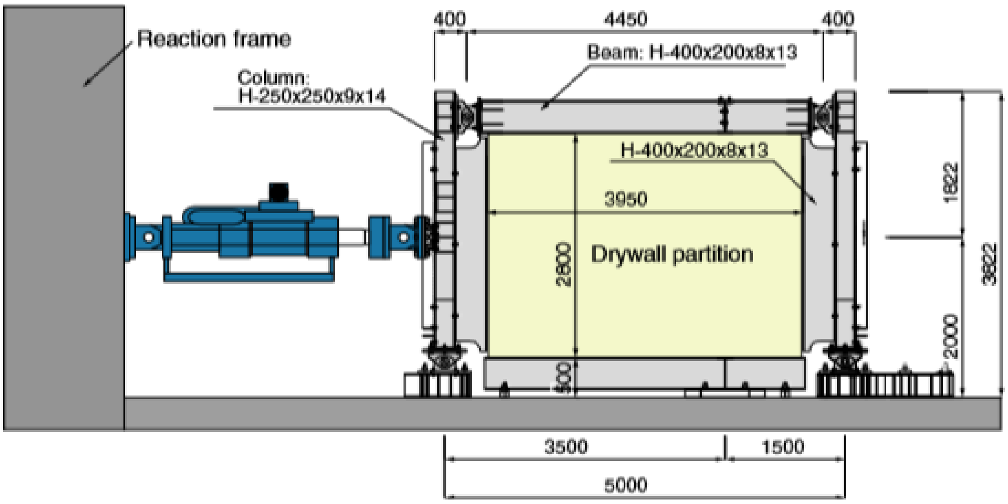

Figure 2.10. Experimental Test Setup- units in mm (Lee *et al*., 2007)

In this type of experimental study, more than one specimen is tested so that checking the systems with different inputs such as different partition and structural frame connection type, various height and width of the walls, including openings or not, various design details with different stud spacing and various layers of gypsum boards. In Lee *et al*.'s (2007) study, four different light-gauge steel-framed drywalls are built inside the RC structural frame and different configurations are created. The damage patterns of drywalls after the tests are illustrated in Figure 2.11. This study is concluded with a repair cost estimation. The repair cost is associated with the story drift ratio of partitions. If the drift ratio exceeds 2%, the repair cost is equal to the initial cost for all types of partitions (Lee *et al*., 2007).

Figure 2.11. Damages After the Tests & Damage Descriptions: (a) Crashing at the top edge and corners and joint cracks; (b) cracks in the panels, deformation of gap and crashing at the corners and top edge; (c) detachments of partitions from the studs (out-of-plane deformation), crushing at almost all edges (Lee *et al*., 2007)

Another experimental study concerning the seismic performance of plasterboard partitions was done by Magliulo *et al*. in 2014. The seismic behavior of innovative drywall systems is observed with the shake table test which causes drywalls subjecting both inter-story drift and accelerations synchronically. In this study, a steel frame is used to simulate real-life scenarios. Eleven different test intensities are checked in terms of inter-story drift demand and acceleration demands. To control accelerations of the partitions, roof and table base, accelerometers are located at the column base, center of beams and center of drywall. For the recorded displacement values, laser sensor records are used.

In addition to experimental studies about the seismic performance of drywalls, the analytical modeling of steel stud gypsum walls was investigated in the literature (Rahmanishamsi, 2015). The studies of Restrepo *et al*. (2011), Davies *et al*. (2011) and Wood & Hutchinson (2014) are examples of analytical studies. In Wood and Hutchinson' (2014) study, a numerical model is developed in the OpenSees modeling platform. At the mid-height of a floor, zero-length springs are located to represent partition walls in the model (Figure 2.12a). Also, for the representation of spring, the material of OpenSees; the "Pinching4" is used. Pinching4 is a single nonlinear uniaxial material that includes backbone point unload and reload response of the material. The uniaxial spring is applied in the longitudinal direction while the out-of-plane force is not characterized. In this study, subgroup and normalized models are developed. Several analyses are performed and results are reflected the truth position regarding the behavior of walls, especially drift ratio of the partitions because drift ratio is associated with physical damage status of the walls. The analytical results are taken according to the different specimens.

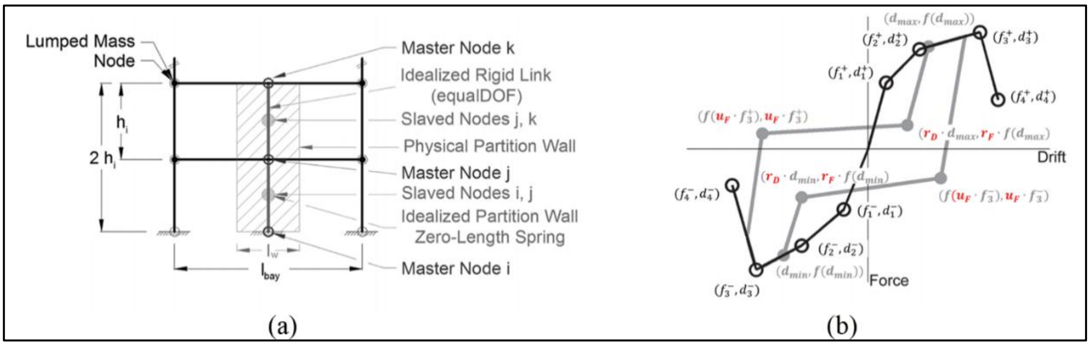

Figure 2.12. The analytical study by Wood and Hutchinson (2014), (a) Idealized drywall analytical model; (b) The Pinching4 material including backbone points in black color and unload and reload response of the material in grey and total half-cycle hysteretic energy

As a summary, the seismic studies of gypsum board partitions in the literature are investigated. The damage states, damage patterns, and their consequences are illustrated in light of the experimental and analytical study.

2.3. Integration of Seismic Design of Non-structural Elements and BIM Technology

The big ratio of the building value is formed by non-structural elements and building contents, therefore, the professions and society give more attention to losses due to the poor performance of non-structural elements during the earthquake. To improve the seismic performance of the non-structural elements, Seismic Performance Of Non-Structural Elements (SPONSE) Association is proceeded by Filiatrault and his colleagues in 2015. The goals of the SPONSE Association are to support the studies about the seismic design of non-structural components, to encourage the education on this subject, to promote the findings and developments, and to consolidate the relationship between different parties like professions, academia, and industry *etc*. that are interested in the performance of the non-structural components during earthquake. Recently, the resilience of building elements in earthquakes is the greatest challenge. The term 'resiliency' gains importance as the main goal of the buildings achieves continuity of services after any disasters therefore in the following part it is shortly mentioned about the significance of the seismic resilience of the buildings.

- **Seismic Resilience of Buildings**

The definition of 'resiliency of built environment' is explained by Liu (2012) as speedily resumable of the building's components and function after a catastrophe. According to Liu (2012), buildings include interconnected many components like structural systems, utilities, facilities of the buildings, the users, infrastructural systems, building contents so on. Thus, the resiliency of the single component is directly linked to the resiliency of all other components of the buildings. Before, while the main target performance of the buildings was the avoidance of collapse of the structural system but lately as Günay and Mosalam (2012) stated, the desired performance levels should provide the resiliency requirements especially for essential and high occupancy buildings like hospitals, residential and commercial buildings, *etc*. Differently from conventional earthquake design principles, in low- medium- high intensity levels of the earthquake, the seismic design philosophy is saving the buildings from any structural and non-structural damage and so the buildings can stay in operation after an earthquake.

Another important step to improve the seismic study of the non-structural elements is utilizing BIM technology. BIM may help to open a good frontier in the automated seismic design of the non-structural elements because the effective seismic design of non-structural building elements depends on good communication between all stakeholders. BIM provides strong coordination and integration. The integration of performance-based seismic design and BIM technology could alter the standard design practices and produce a new flow for seismic design. The required data to develop the seismic assessment and design is provided by an intelligent building information model. With the combination of structural and non-structural elements in the same model, the optimum design solution is classified. Hence, the integration of these two systems in a shared model is very useful to develop a new method for the seismic design of the building elements (Perrone and Filiatrault, 2017).

Also, there is a general lack of accountability and responsibility by engineers and architects as to has the design and maintenance responsibility of the non-structural elements because these elements are in the intersecting area of engineering and architecture. With the help of the shared working platform of BIM, required information and details about all these elements are available in a compact model. Therefore, required data can be taken from building information model in the seismic design and installation of non-structural elements.

2.3.1. Earthquake Studies of Non-structural Elements via BIM Tools

The seismic performance of the non-structural components is nowadays an important subject to ensure the desired seismic activity of the buildings. In the taking seismic precautions for the non-structural elements, the detailed information of the building is vital to enhance the quality of the seismic analysis and design. Therefore, in the literature, a few studies with regard to seismic design of non-structural elements, benefits from Building Information Modelling (BIM) Technology since as Welch, Sullivan and Filiatrault (2014) mentioned that the required worthful data for both structural and non-structural elements of a building are provided by BIM to be used for seismic risk assessment and automated seismic design of non-structural components (Perrone *et al.*,2017).

In Welch *et al.* (2014) study, it is explored whether the developments in BIM technology could reduce seismic risk. The writers explained how BIM could supply to the seismic risk assessment within the Pacific Earthquake Engineering Research

Center's (PEER) Performance-Based Earthquake Engineering (PBEE) [4] methodology. According to researchers, BIM within a seismic assessment could provide;

-valuable information to remove uncertainties and improve the quality of the analysis

-records about installation details of components and equipment for seismic loss assessment

-involving seismic consultants (structural engineers) into the design and installation of mechanical and architectural contents

-rapid calculation of component quantities for the correct estimation of the repair cost

-developing the viability of leading seismic risk assessment with specialized tools thanks to its interoperability capabilities

-central virtual platform with an integrated model that supplies easily accessed multi-disciplinary data for a privatized seismic risk assessment program.

Welch, Sullivan, and Filiatrault (2014) claimed that the contribution of BIM to comprehensive seismic risk assessment can improve by exporting data to external specialized risk assessment software. BIM tools interpret the data for structural components, architectural elements, utility services, and building contents and the required information like seismic risk can be reached via operating external programs regarding specialized for seismic loss assessment, compatible with the central BIM platform. BIM platform is used as a central information store and thanks to master building repository, needed information for seismic loss assessment is provided by BIM. The framework is illustrated in Figure 2.13.

Another study by Perrone and Filiatrault (2017) emphasized the potentials of using BIM technology for seismic design and/or assessment. The writers believed that in the

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[4] PEER-PBEE: Pacific Earthquake Engineering Research Center's (PEER) research program supplies data and software tools to support Performance-Based Earthquake Engineering (PBEE) methodology. This includes four stages: Facility Definition, Structural Analysis, Damage Analysis, and Loss Analysis. In the last stage, loss estimation is mostly related to non-structural elements.
Source: https://peer.berkeley.edu/research/pbee-methodology & Welch *et al.*, 2014.

seismic design of non-structural elements via BIM can open a new vista in PBEE. The valuable detailing data of all components are available in the intelligent building model and this is so important in PBEE assessment for the definition of the damage characteristics and estimation of the repair cost and time. To display the utility of using BIM for the automatic seismic design of the non-structural elements, a case study is studied on the fire suppressant sprinkler piping systems by Perrone and Filiatrault (2017).

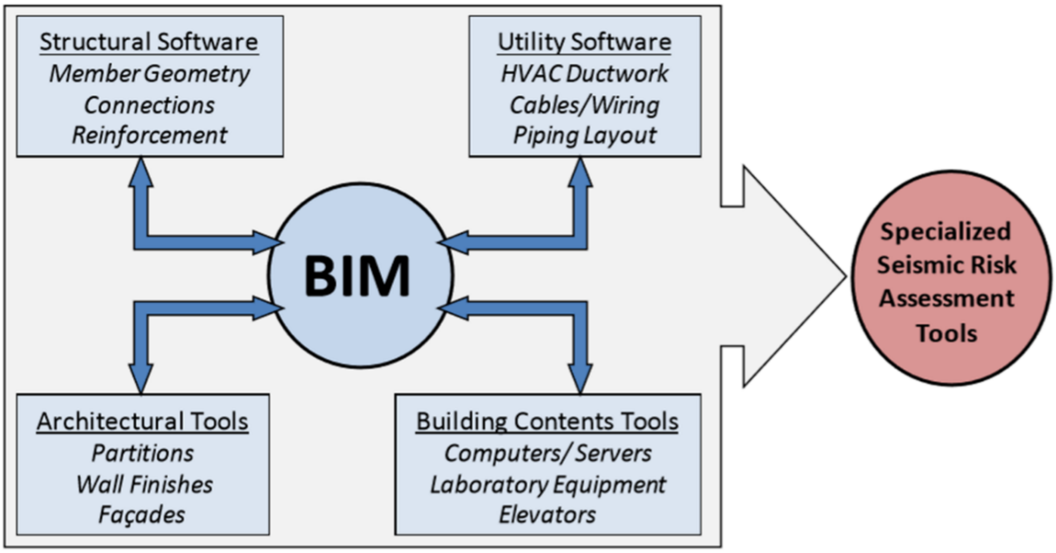


Figure 2.13. BIM, as a central data repository, enables data exchange between different disciplines and it is compatible with specialized external software for seismic risk assessment (Welch *et al*., 2014)

This study includes two important objectives;

i. Creating a framework by using data in building information model for automated seismic design of the non-structural components,

ii. Justifying operability of the framework with a case study on the automated seismic design of sway braces system for fire sprinkler piping systems using BIM.

The developed framework is illustrated in Figure 2.14. According to the types of elements, various specific tools are used like braces, anchorage, *etc*. For all non-structural components, there is a unique platform respectively. That is, thanks to data in the building model about elements, the problem of seismic design of each non-structural components can be solved.

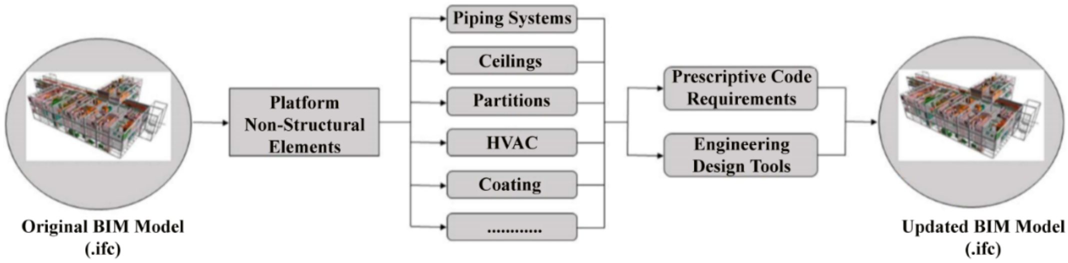


Figure 2.12. The framework for the automated seismic design of non-structural components using building information model (Perrone *et al*., 2017)

In this study, it is created a flow chart of the methodology for automated seismic design of the fire sprinkler piping systems (Figure 2.15). As an initial stage, the fire sprinkler system layout is extracted from the building information model in IFC format. Then, to specify all geometric coordinates of the pipe joints, IFC format is uploaded to CAD environment. The next step requires a special environment since a seismic design tool is developed to satisfy seismic design requirements for each type of non-structural components. The coordinates of the sprinkler piping system are imported in .txt format to seismic design tool developed with Microsoft Excel Visual Basic for Applications (Excel VBA) which is “Seismic Analysis of Piping Systems for BIM Application” or “SAPIS-BIM”. The seismic design tool is created to check the seismic design requirements for the installation of sprinkler systems (Perrone *et al*., 2017).

Figure 2.15. The flowchart of the methodology for the automated seismic design of the fire sprinkler piping systems (Perrone and Filiatrault, 2017)

The most important part of the study is evaluating the seismic demand with the application of National Fire Protection Association NFPA 13: Standard for the Installation of Sprinkler Systems in SAPIS-BIM. According to the lateral seismic force, the number of braces and distance between sway braces is automatically computed for each pipe by SAPIS-BIM in the light of NFPA 13. Finally, the seismically designed braces are exported to CAD environment in .txt version to specify the coordinates of the braces. Then from CAD platform, results are sent to Tekla BIMsight, which is a BIM tool to view models, by using IFC file. The methodology of this study could be extended for the different typologies of non-structural elements by defining a platform for automatically seismic design. This can open a new era in PBEE (Perrone *et al.*, 2017).

2.4. Critical Analysis of Literature Review

Building Information Modelling (BIM) technology in the Architecture, Engineering, and Construction & Operation (AEC/O) industry have great potentials for the project realization and operation process. The benefits and compatible platforms of BIM technology are also mentioned in the reviewed literature. Interoperability for the data exchange is emphasized on behalf of the collaborative teamwork during the project and construction process throughout the literature. All capabilities, advantages and working principles of BIM, explained in the literature, are promising for the industry problems and future expectations from BIM technology. In this research, it is tried to utilize from the development of BIM as an enabler tool for the seismic evaluation of the non-structural elements. As exhibited in the following quotations and the reviewed literature, the seismic performance of the non-structural elements in the buildings is a critical issue in terms of behaviors during the earthquake.

In 1914, Professor Modesto Panetti from Instituto Superiore di Torino wrote: ‘‘ …the effects of earthquakes on **structures** are in fact a structural dynamics problem, which is much too complicated to address…’’

In 2015, the earthquake engineering community still believes: ‘‘ …the effects of earthquakes on **nonstructural components** are in fact a structural dynamics problem, which is much too complicated to address…’’

In addition to these quotations, recent earthquakes showed in the literature, while the buildings survived without any structural damage, it can be observed the widespread damages resulting from non-structural’ failure after the earthquakes. The damage to any type of non-structural elements threatens life safety and causes property loss and functional loss. Therefore, as mentioned before, the failure of the non-structural elements is a serious problem for the PBEE principles. ‘‘Resilient design’’ of the non-structural elements becomes vital and the buzzword in the industry.

Through the literature review, studies showed that it is needed a real step to explore new technological platforms for the seismic design of the non-structural elements because these elements are not tested in the design stage before the installation. Seismic behavior of non-structural elements is only observed during the earthquake and this is not a proper way for the performance-based earthquake engineering. In the reviewed literature, the seismic behavior of gypsum board partitions, mostly used components of the architectural elements, is focused. Experimental and analytical studies are investigated about the seismic response of drywall systems. The experimental studies are restricted in a limited number of wall elements but all partition elements should be check before the installations since the buildings are strong as much as their weakest link. For the analytical studies, the modeling and analyzing each drywall in the related software requires plenty of time and more people. Moreover, correctly sharing the outputs from the analysis is very difficult for each partition. At this point, asserted capability of BIM about reliable data exchange method could make analytical analysis process possible, the faster and more trustworthy in a short time with a couple of people.

In Figure 2.16, the summary of the literature study is shown diagrammatically. Consequently, the integration of Building Information Modelling (BIM) technology and seismic studies of non-structural elements are considered as a promising way in this research. Therefore, in the last part of the related literature, researches, which integrate seismic studies of non-structural elements and BIM technology, are explored.

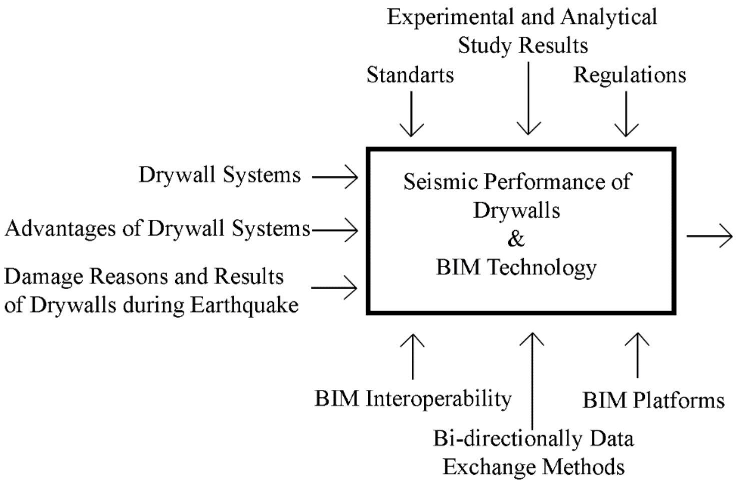


Figure 2.16. Schematically shown what is about the reviewed literature

There is only one study in the literature about the seismic design of non-structural elements and BIM belonging to Perrone and Filiatrault (2017). In their research, authors asserted that an automated seismic design way for the sprinkler system via using BIM technology is possible. The authors suggested extending this research through the development of similar BIM compatible tools for the automated seismic design of other typologies of non-structural elements. In Perrone and Filliatrault's study, as a data exchange method, IFC file format was used. The flow of the working process of their study includes .CAD environment to exchange data between different software applications. The aim of this study is enabling from BIM to produce and share seismic data for the automated seismic design of drywalls with an appropriate workflow to BIM principles.

CHAPTER 3

RESEARCH MATERIAL AND METHOD

In this chapter, the material and methodology of this study are explicated. In the first section, data flow methods for AEC/O (Architecture, Engineering, Construction, and Operations) sector are presented. The important and selected method for data exchange in BIM technology, Application Programming Interface (API), is investigated. Also, another method for data exchange, Industry Foundation Classes (IFC) data model, are covered. In the second section, the structural design inputs and process of office buildings for case studies are introduced. Selected BIM compatible tools, which will be used through the research, are explained. The seismic parameters, effecting the design of drywalls, are mentioned. Finally, an explanation of three case studies is mentioned, and Chapter 3 ends with a flow chart of the methodology of this study.

3.1. Bi-directionally Data Exchange Methods in BIM Technology

Successful and effective communication and collaboration between stakeholders by adapting BIM technology is an important step for the Architecture, Engineering, Construction, and Operations (AEC/O) sector. There are several data exchange methods developed in the project realization throughout history for the sake of interoperability (Goldstein et al., 1998). Recently, Application Programming Interface (API) (da Silva et al., 2017) and Industry Foundation Classes (IFC), which is an open format (Ren et al., 2018), have been preferred for exchanging project data. Exchanging process should occur bi-directionally to comply with BIM concept. In other words, all revisions, analysis results and outputs should turn back to the main building model to sustain an integrated project design process. The bi-directional data transition schematically explained in Figure 3.1.

Figure 3.1. Bi-directional data exchange will be checked by two methods: API and IFC

The level of availability and reliability of two data exchange methods, API and IFC, is tested with a building model. The building model is created in Revit 2019 software. The reasons why Revit is chosen as an authoring tool are that being the production of the growing Autodesk company and enabling the various data exchange methods. Ignatova et al. (2018) specified that Revit Software is widespread in information modeling technology since Revit provides functional studying templates for different disciplines and eases data exchange among applications within BIM concept. Additionally, project data can be stored safely in the Revit neutral file format (.rvt). For these reasons, this study is carried out using Autodesk Revit software as one of the main authoring tools. The model created in Revit was then sent to different BIM compatible structural analysis tools such as Robot Structural Analysis which is also Autodesk, ETABS which is one of the most used tools in industry and Sofistik which is directly connected to Revit interface. Afterward, in the interface of analysis software, the sending model was controlled if there was data loss or not. If there is no trouble about data transition, the basic analyses can be done to observe the process for this study. Then, the obtained analysis results were sent again to the main building model to share with all team members. If this loop operates smoothly with the help of API extensions or IFC file format, BIM-based workflow could encourage optimization and automation of the construction process in the AEC/O sector.

Building Model

Two data exchange methods among different applications; API and IFC, are checked by using the studying model through the architectural and structural design case. In this part of the study, one of the structural models, produced for the analysis sections, is taken as a sample model. This model is an office building, including eight stories in 4 meters story height without a basement. Three bays in each direction are supported by reinforced concrete frame elements in the perimeter and shear wall in the core. In Figure 3.2, the developed model in Revit Structural Template is shown physically and analytically. Revit structural template allows creating an analytical model automatically as a representation of a physical model. Analytical model in Revit facilitates data exchange with other structural analysis tools since the connection of all Revit elements, nodes can be controlled before the generated model in the different analysis platforms. The analytical model is also adjusted and edited manually by managing nodes at the connection of frame elements (Johnson & Fudala, 2012; CSI Documentation, 2018).

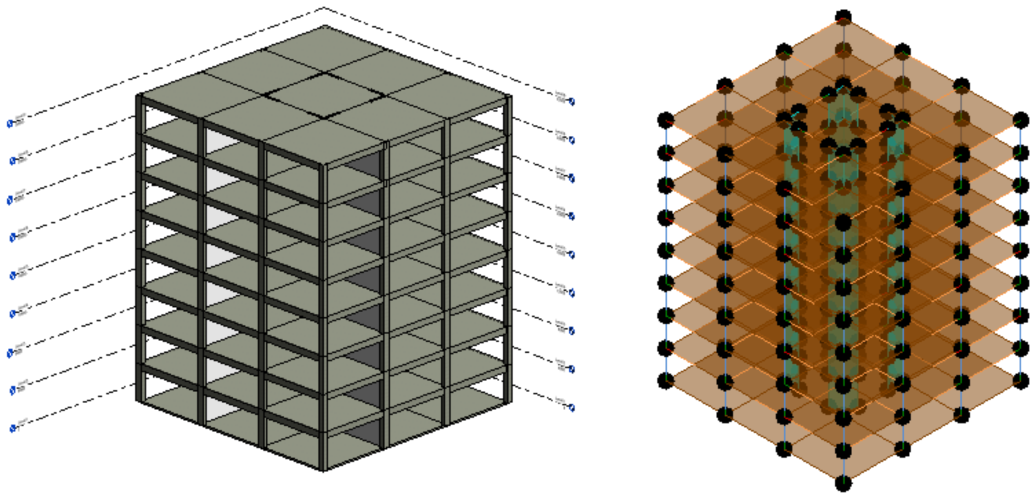


Figure 3.2. Physical (a) and analytical (b) models produced in Revit

Elements in the building model are created as an intelligent object by means of BIM concept. The elements in the model are not just a geometrical representation like size, width, height, orientation, volume, shape, *etc*. but also they include non-geometrical attributes (parameters) like material, cost, manufacturer, specification, *etc*. The physical and functional characteristics of elements, their material properties, and design parameters are clear in the object-oriented model. Therefore, it is expected that all attributes of each element are exchanged reliably among software. The building model also includes annotation elements like grids, levels, etc. so this type of model element should be exported and imported in target applications, too. API and IFC file format method are investigated. The possibilities and limitations of the two methods are evaluated.

3.1.1. Application Programming Interface (API) Extensions and Supplements

Application Programming Interface (API) supplies direct links between different application programs and allows exchanging bi-directionally among independent software by creating specific tools and add-ins. API is used for developing specialized software extensions and supplements to increase the utility of BIM solutions. As Yousefzadeh *et al*. (2015) assert, the high quality of the data exchanged with API extensions allows a successful and integrated project life. However, it should not be forgotten that direct links just work specifically for target applications so a developed direct link operates only for specific software platforms and their specific versions. Thus, an extension is used for a limited transition path between specified programs. API-based extensions and supplements are developed by the production firm of software and it’s partnerships in order to exchange information between target applications like Revit and its target application (Maia *et al*., 2015).

In the Revit API, data importing and extracting tools, called plug-ins, are created. The plug-ins are used for especially organizing the construction process, as well as improving the interoperability and productivity, allowing the applications for calculations and run commands through building tasks by team members from different disciplines. BIM users encourage the development of plug-ins for sharing project data because plug-ins improve the synchronization of the related data in the target external application. Besides, it is taken advantage of plug-ins in the area of cost estimation, business schedule, energy efficiency and sustainability analysis, and using different computational tools (da Silva *et al*., 2017). Ignatova, Zotkin, and Zotkina (2018) asserted that the API method enables internal analysis with extracting data from native building information models and so the analysis results stay in the main building model.

Autodesk Revit Structure ←→ Autodesk Robot Structural Analysis Professional

In this section, the model transition via a direct link between Revit Structure and Robot Structural Analysis Professional is focused on. Revit and Robot Structural Analysis software are the products of the same firm (Autodesk) hence it is facilitated with a direct link for transferring data. When Robot Structural Analysis software is downloaded, it is automatically associated with the Revit platform. The icon of the Robot Structural Analysis Professional appears as a tool in Revit structural analysis interface under the 'Analyze' tab. By clicking on this tool, the integration link with Robot Structural Analysis dialog box is opened (Figure 3.3). This dialog box allows selecting the direction of data flow. ''Send model'' option is chosen for the first time of data exchange.

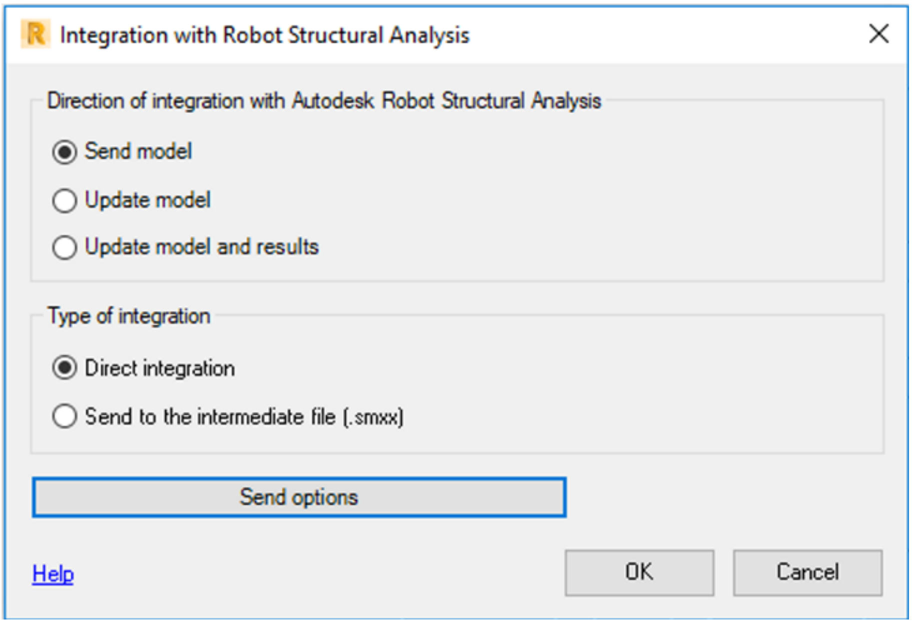


Figure 3.3. The data flow direction, integration type and send options can be selected in the dialog box in Revit interface

Direct integration link between applications, the data transfers quickly from Revit to Robot Structural Analysis Professional or vice versa. In the interface of Robot Structure, which is a finite element analysis software, the model should be checked regarding whether data loss or not. In the API data exchange method, the sent structural model can be directly used for analyzing, design and simulation in Robot because potential errors can be eliminated by checking the analytical model in Revit. The building model in Revit includes grids, levels, structural columns and beams, shear walls, floors and their material properties, defined loads and load cases, and member end releases. All these elements and their attributes are sent to Robot via direct link integration. In the Robot Structural Analysis platform, the model can be updated by defining final load cases and combinations and adding advanced analysis parameters. In Figure 3.4, Revit models and structural models in Robot which is generated from a direct link is shown.

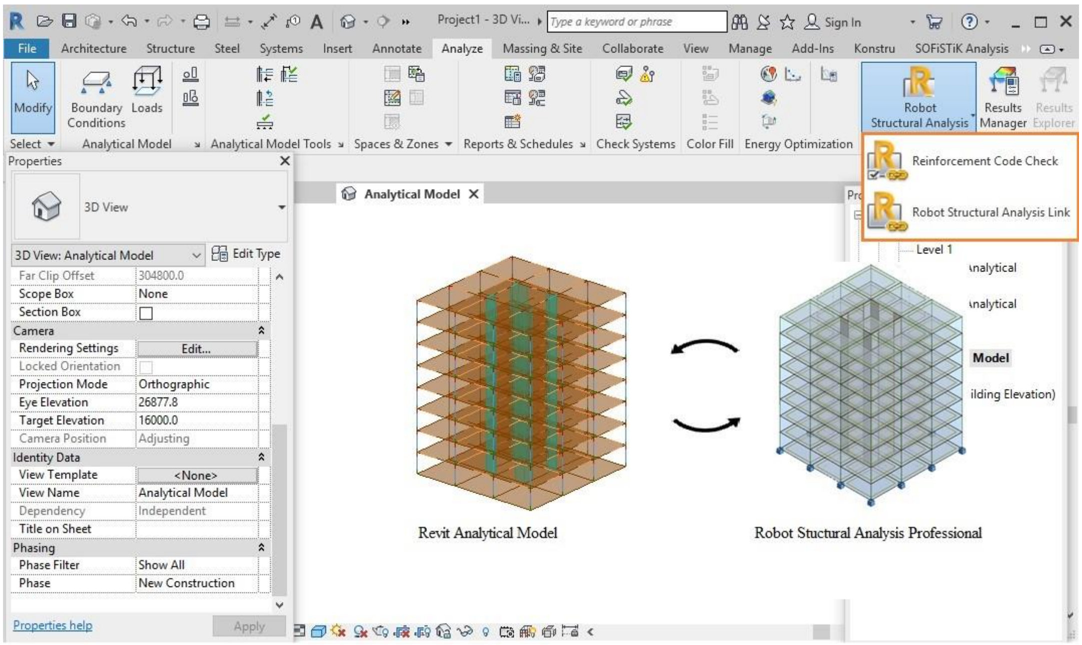


Figure 3.4. Robot Structural Analysis Link for bi-directional data exchange

The model sent to the Robot platform is checked and approved before the structural analysis. The grids and levels, dimension and material properties of structural components, the connection of the frame elements are successfully exchanged. In other words, the structural model is automatically obtained without any warnings. After the data exchange process with a direct link, loads and load cases are defined and then calculations can start. In this study, the structural model is analyzed for dead load cases to be as fast as all get out because the main aim of this section is investigating the data exchange capabilities of the API method. Therefore, a simple analysis case is set in Robot, then the analysis results are tried to send back to Revit to update the building model based on analysis results. For returning the data to the Revit model, the direction of integration should be chosen as ''update model and results'' and so all amendments and results can be taken to the Revit building model.

In Revit, thanks to 'result manager' and 'result explorer' add-ins tools () details about the updating process are saved and the structural analysis results are visualized.

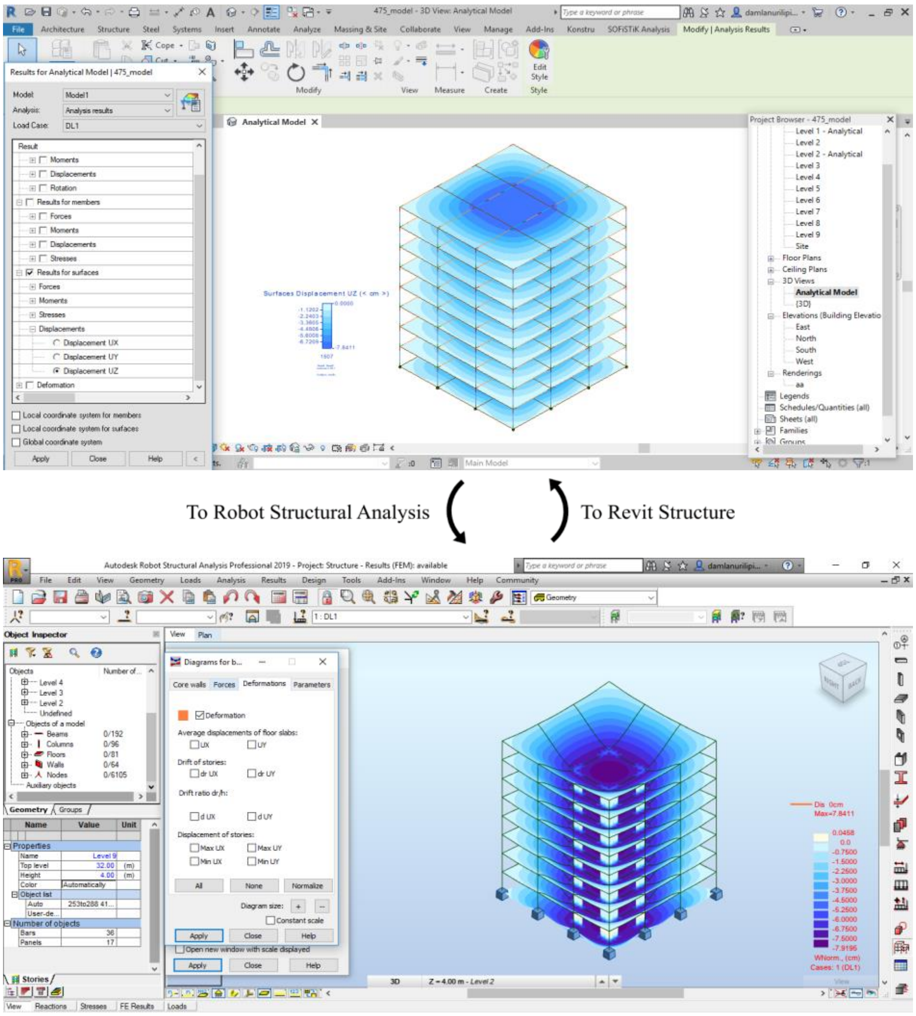


Figure 3.5. The bi-directional data flow smoothly between Revit and Robot Structural Analysis Professional

The design changes and analysis results for the base, members, and surfaces are transferred back to Revit smoothly. According to design changes and analysis results, the physical model is updated. This proves that between Revit Software and Robot Structural Analysis Professional integration direct link works and supports interoperability and so it is possible to collect all updated data in a building model. The bi-directional data flow is promising for the third level of BIM maturity level because the bi-directional data exchange improves the productivity of the project process, decreases communication problems, provides efficient coordination, orientates to the best design option, and accelerates the decision-making process. In summary, coordinated working principles are encouraged by direct integration among Robot and Revit software. API method facilitates the development of operation speed and efficiency of the project process, as well as eliminates errors and problems. In other words, API, which is the state-of-art data exchange method, supports bi-directional data flow, a collaborative study between Revit software and Robot Structural Analysis Professional.

Autodesk Revit Structure ←→ CSI ETABS

ETABS is structural and earthquake engineering software, produced by Computer & Structures, Inc. (CSI). The capabilities of the software are modeling the structure, analyzing and designing process and reporting outputs. ETABS has been promoted as an integrated software package to be more productive for the industry so the data exchange between ETABS and Revit has been improving. CSI develops an API, which is a common programming language as mentioned before, to increase the utilization of ETABS in the concept of BIM. In the integration between ETABS and Revit, a plug-in has been developed, called CSiXRevit. This plug-in provides bi-directional data flow between ETABS and Autodesk Revit Structure. CSiXRevit is added to the Revit interface in the Add-ins tab as an external tool when it is downloaded. Thanks to this tool, a common file format ‘‘.exr’’ for intermediate data exchange is created. Then, .exr file is exported from Revit and imported to ETABS. In the data transition process, grid lines, story levels, materials, structural frame elements, walls and floors (if they are not slanted and sloped), defined loads and load cases except area loads are exported from Revit Structure to ETABS (CSI Documentation, 2018). The level of serviceability of CSiXRevit is checked by exporting the building model created in Revit Structure (Figure 3.6).

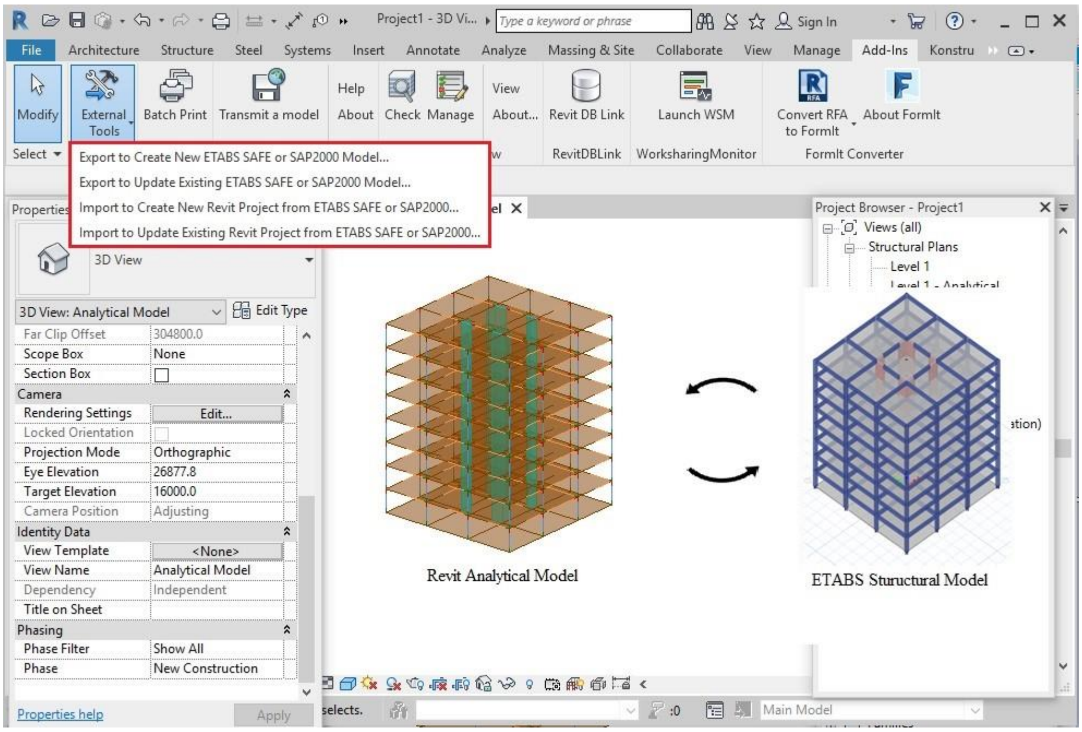


Figure 3.6. CSiXRevit, Bi-directional data flow plug-in for Autodesk Revit

In the imported model to ETABS, structural elements, their section properties, nodes, dimensions and materials definition are controlled. CSiXRevit plug-in for data flow from Revit Software to ETABS works properly so the importing model to ETABS can directly be used for analyses. After loads and load cases are defined, the analysis runs in ETABS. According to analysis results and design changes, the structural model is exported in Revit Structure .exr file format from ETABS to Revit software. Unlike Revit- Robot integration link, in the updated model, the analysis results are not seen in the Revit interface. Therefore, to supply the bi-directional data exchange chain, BIM server, ‘‘Konstru’’ is developed. It is aimed to solve interoperability problems between different software with the creation of Konstru by extracting, cleaning, converting and visualizing data in the design and structural engineering process. Data transition problems from ETABS to Revit can be solved via this the web-based environment. The outputs from ETABS are sent to Konstru whose interface also allows visualization model and analysis results. From the Konstru tab in the Revit interface, the analyzed model is also transferred from web-based Konstru plug-in to Revit software. Thus, outputs are sent to Revit and the results are revealed in the Revit building model. Although Konstru has the capability of extracting all building elements of the building model among various software such as Tekla Structure, Revit, Rhino, Grasshopper, Bentley Ram, Sap2000, ETABS and Excel, it cannot support all types of analysis results view in the Revit model. Konstru is able to show only force values for the frame elements so Konstru plug-in is limited to exchange all results between two different applications

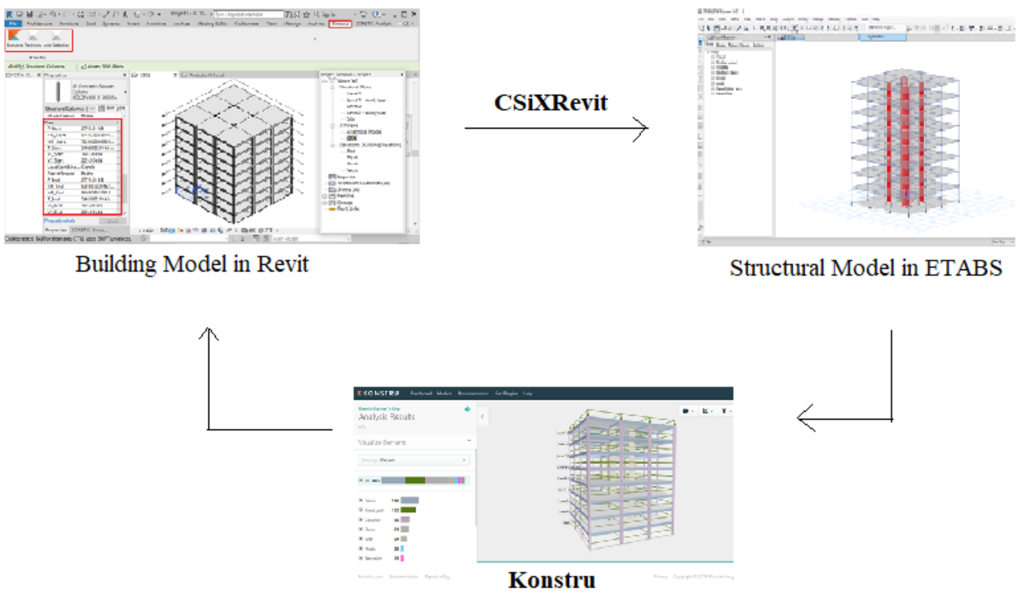


Figure 3.7. The data flow path between Revit and ETABS by the help of two plug-ins; CSiXRevit and Konstru

Autodesk Revit Structure←→ SOFiSTiK Analysis Software

SOFiSTiK is a structural analysis and design software which provides fully collaborative data flow within Autodesk Revit. The extension application of

SOFiSTiK that is SOFiSTiK FEA Extension generates a finite element model in the SOFiSTiK structural analysis desktop interface by using the analytical model of Revit software. When the SOFiSTiK application is downloaded, the SOFiSTiK FEA app directly appears as a tab in the Revit interface. Hence, the analytical model can be directly analyzed in the Revit interface by using the 'analyze' tool under 'SOFISTiK Analysis' tab if loads and load cases are defined (Figure 3.8).

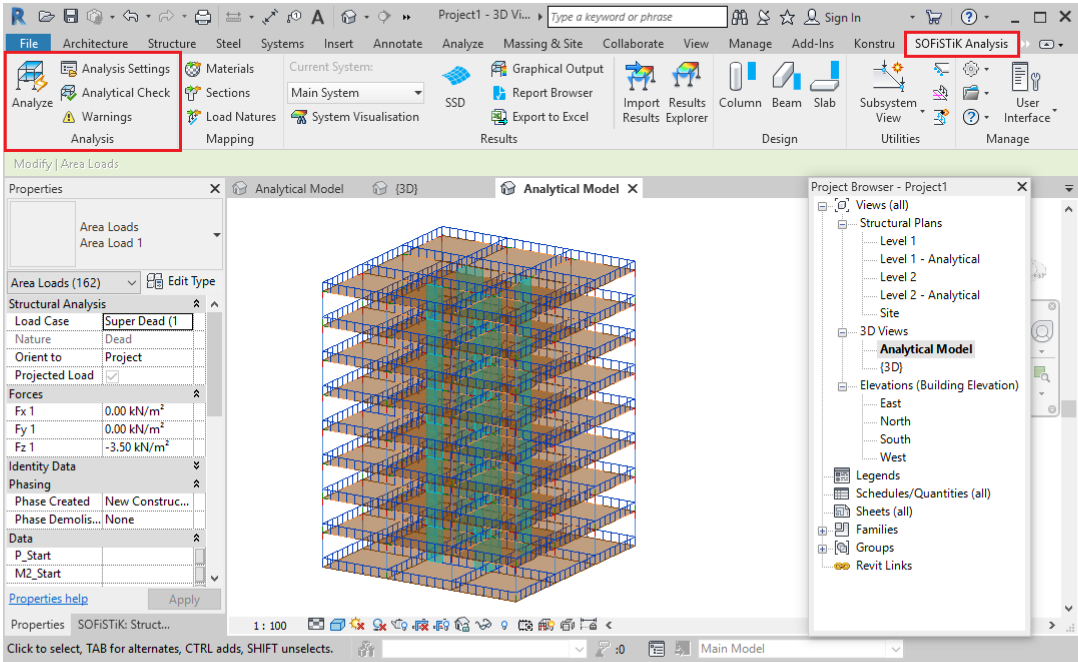


Figure 3.8. The finite element analysis with SOFiSTiK FEA Extension in Revit interface

If Revit analysis case is not satisfied, the generated model in Revit is sent to SOFiSTiK Structural Desktop (SSD) with a direct link and new analysis cases are defined in the SSD interface. After calculations end, the results can be investigated in Revit interface by using ''Import Results and Results Explorer'' tools or results can be examined in the SSD interface (Figure 3.9).

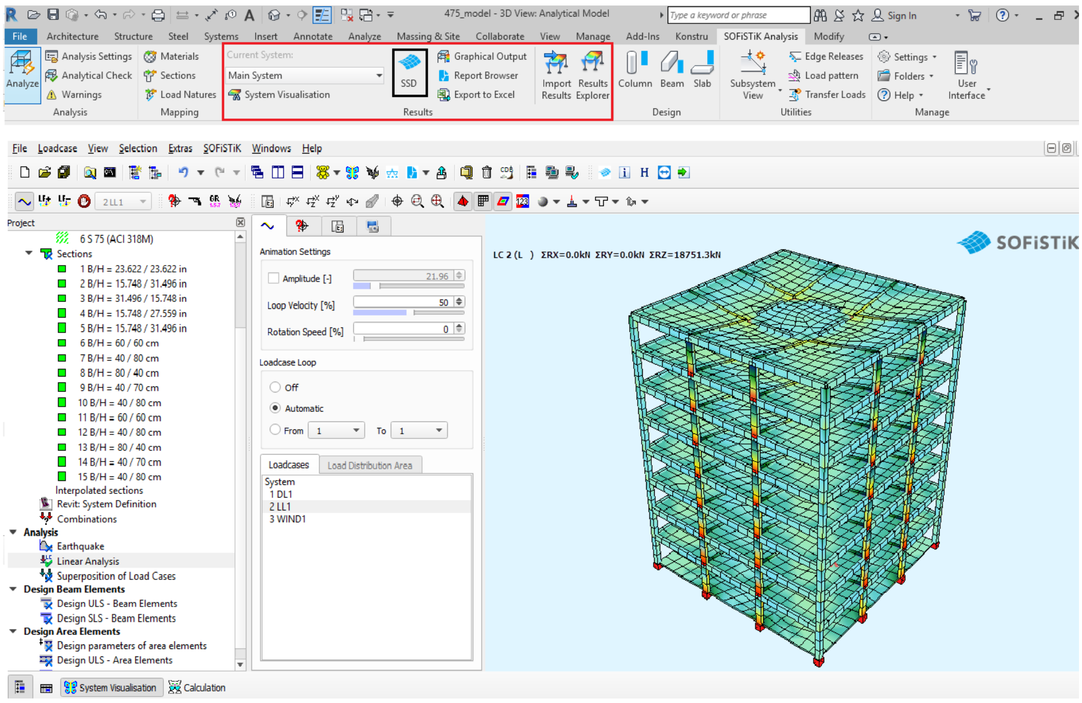


Figure 3.9. Direct integration with SSD application by using Revit SOFiSTiK tab tools

To sum up, in this section it is exhibited how benefitted from the API method for data exchange in the idea of BIM. Different structural analysis software is preferred to observe various software solutions for bi-directional data flow. Although some plug-ins, add-ins, and extensions are created for the smooth data exchange bi-directionally, still there are some leakages needed to develop. However, API could be the best and trustworthy way for bi-directional data flow between two different applications. Therefore, there is no doubt that in the near future, API method can become the best way for the development of BIM maturity level and so in this research, API method is preferred for the data exchange among different software applications.

3.1.2. Industry Foundation Classes (IFC) File Format

Industry Foundation Classes (IFC) is a common file schema to exchange data. It is provided by buildingSMART International. It is a neutral data exchange model for different stakeholders during the project life-cycle. IFC model, which is an expandable set of data of building models, plays an important role for bi-directional data flow between different software. The model includes a wide range of entities regarding both building elements like window, door, slab, furniture, *etc*. and business tasks such as construction schedule and cost, activities, organization, *etc*. Objects in the IFC schema are placed according to their relations. Object types, classification, attributes, materials, geometry, properties in the IFC ''framework model'' can be used for the representation of the building model. All physical elements are nested in the IFC structure with their different entities. As an example, IFC schema of a wall definition (seen in Figure 3.10) covers entities such as IFCRoot, IfcObjectDefinition, IfcDefinition, IfcProduct, IfcElement and IfcBuildingElement (Sacks *et al*., 2018).

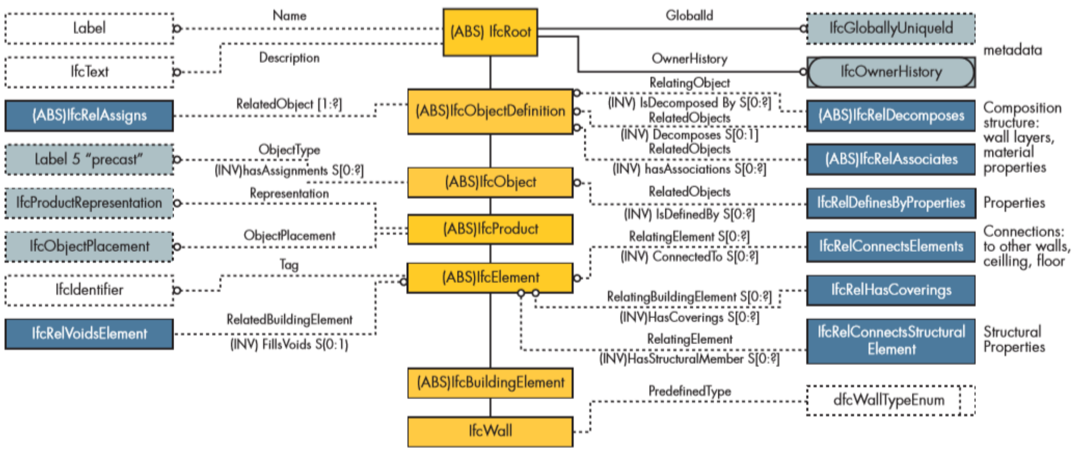


Figure 3.10. Representation of a wall element in IFC schema (Sacks *et al*., 2018)

IFC platform contains architectural, structural, mechanical, electrical and plumbing data therefore in the IFC model, there are various dictionaries to be able to interpret the data. Hence, during the data transfer with an IFC file, first of all, the exchanged data should be interpreted in terms of data category, and afterward, the model can be converted to the compatible data in related dictionaries (Lai and Deng, 2018).

In different BIM software, importing and exporting an IFC file can cause data loss and misleading changes since different software supply different properties in their modeling (Ren *et al.*, 2018). The representation of the geometry, property, and relations of the objects can be described diversely so exchange between different tools causes inconsistent models. Moreover, software tools cannot be defined as some objects belonging to other disciplines owing to have a differential domain (Lai *et al.*, 2018). In the following section, the data exchange with IFC data is examined among different software tools.

Autodesk Revit Structure ←→Autodesk Robot Structural Analysis Professional

As the mentioned previous section, Revit and Robot Structural analysis tools are the products of the same company (Autodesk). However, the data exchange process between these two applications by using the IFC file format does not work properly. In the Revit interface, the building model is exported to the IFC file format and then it is imported to Robot Structural analysis. During the import operation, no warnings and errors occur but some elements are not transferred. The column elements are not imported to the structural analysis tool (Figure 3.11). Also, in the imported model, connections of frame elements are misleading. IFC file format does not transfer joint information.

IFC file data exchange method between Autodesk Revit and Autodesk Robot Structural Analysis software does not work effectively. It is not possible to run an analysis with this imported model. The reason why elements are not read in the Robot tool may be IFC formulation and lack of Robot data readability. Therefore, the IFC data exchange method is not preferred between Revit and Robot Structural Analysis tool.

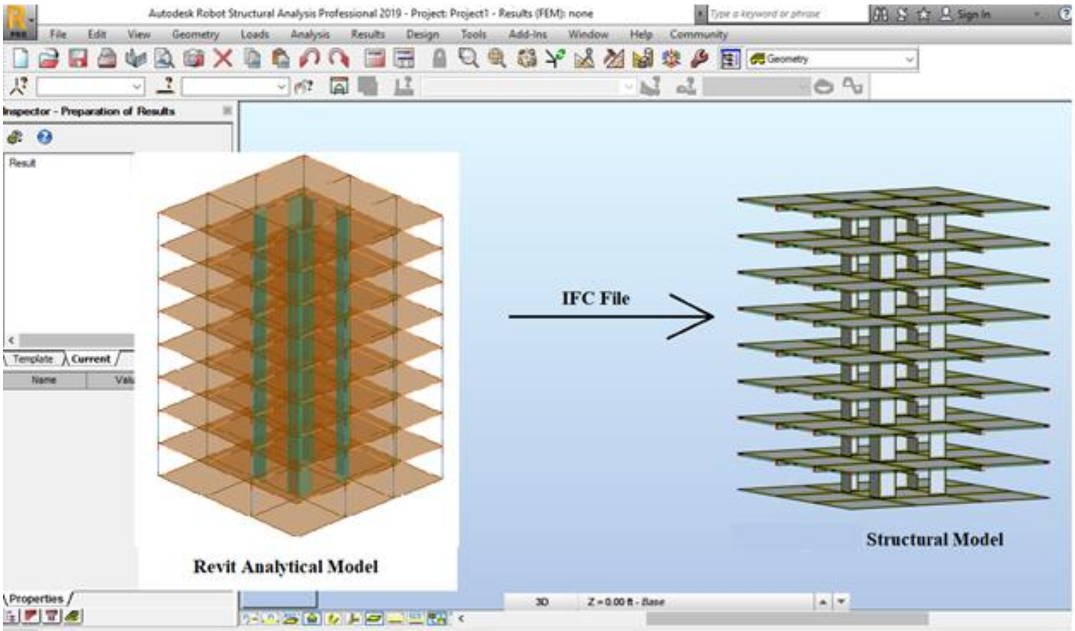


*Figure 3.11.*Misinterpreted Robot Structural Model via IFC file

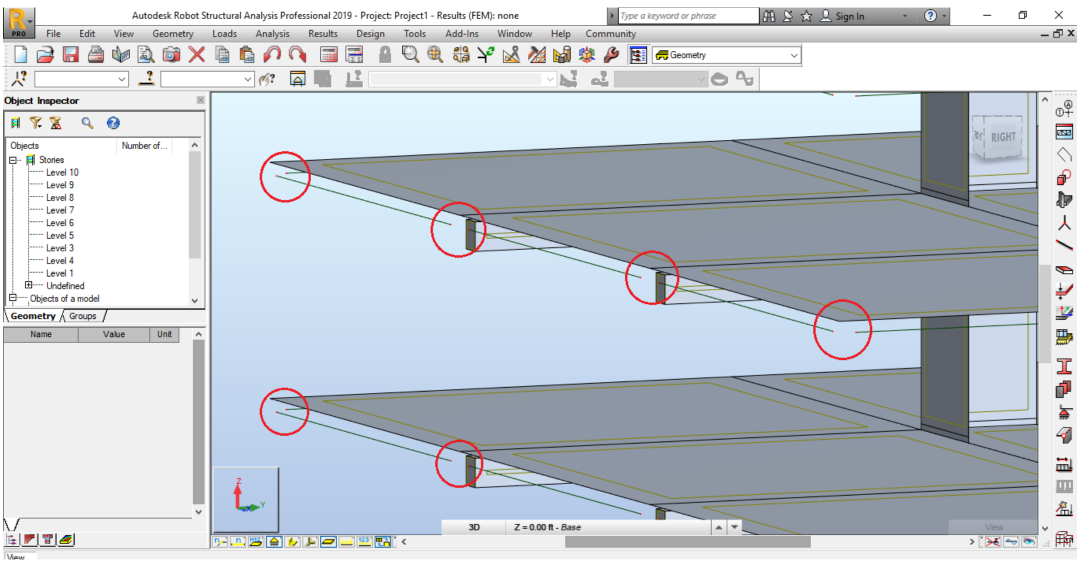


Figure 3.12. Failed connections in Robot Structural Analysis

Autodesk Revit Structure←→ CSI ETABS

ETABS is a commonly used finite element analysis software in the industry. In this section, data exchange between Autodesk Revit and CSI ETABS by using the IFC file format is checked. The building model in Revit is exported to IFC file format and then IFC file is imported to ETABS. During the import operation process, ETABS gives 257 warnings about data transition. Some elements, section properties of the elements, material property are missing in the structural model (Figure 3.13). Also, similar to Revit- Robot data exchange results with an IFC file, the connections of frame elements is problematic in the imported model. For these reasons, the IFC file data exchange is not efficient between Revit and ETABS.

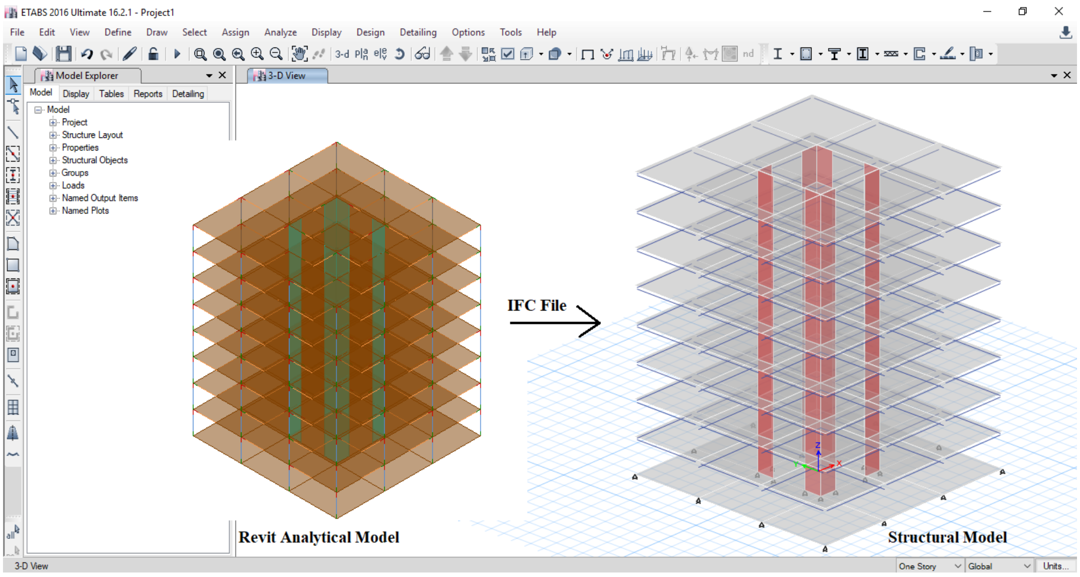


Figure 3.13. Misinterpreted ETABS Model via IFC file

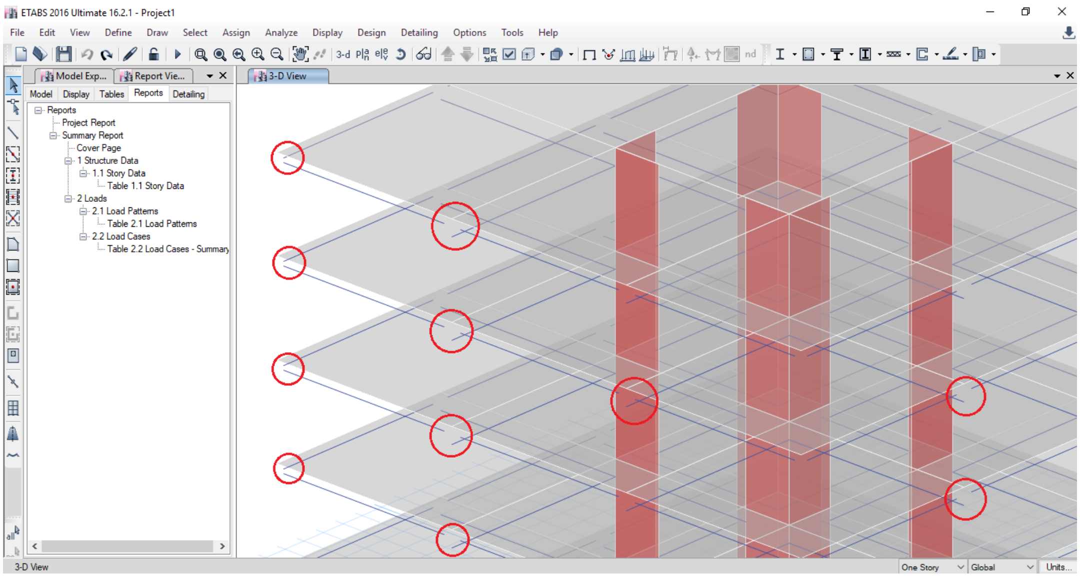


Figure 3.14. Failed connections in ETABS model

3.2. Research Material

In this section of the study, three case models are introduced and their reinforced concrete member design checks are accomplished. Then, BIM compatible tools used throughout this research are mentioned. Lastly, the limiting values for the seismic design in terms of acceleration, force and inter-story drift ratio demands, are investigated.

3.2.1. Design and Check of Case Models

In this section of the study, two office buildings with different reinforced concrete structural systems designed by different seismicity levels, are introduced. The structural systems of the same office buildings are developed according to design and maximum credible earthquakes; 475-year and 2475-year return periods, respectively to observe various seismic performance levels. A typical eight story (mid-rise) office building with 4 meters floor height is empirically designed in İstanbul- Turkey. The architectural design of the generic buildings is inspired from ‘‘Nida Kule in Ataşehir-İstanbul’’. The plan of Nida Kule is reinterpreted and redesigned symmetrically both in x and y axes. The focus elements in the architectural design for this study, which are the gypsum board partitions or drywall, are used to separate the different offices. In the following figure, the typical floor plan is illustrated with each drywall under analyses in red color (Figure 3.15).

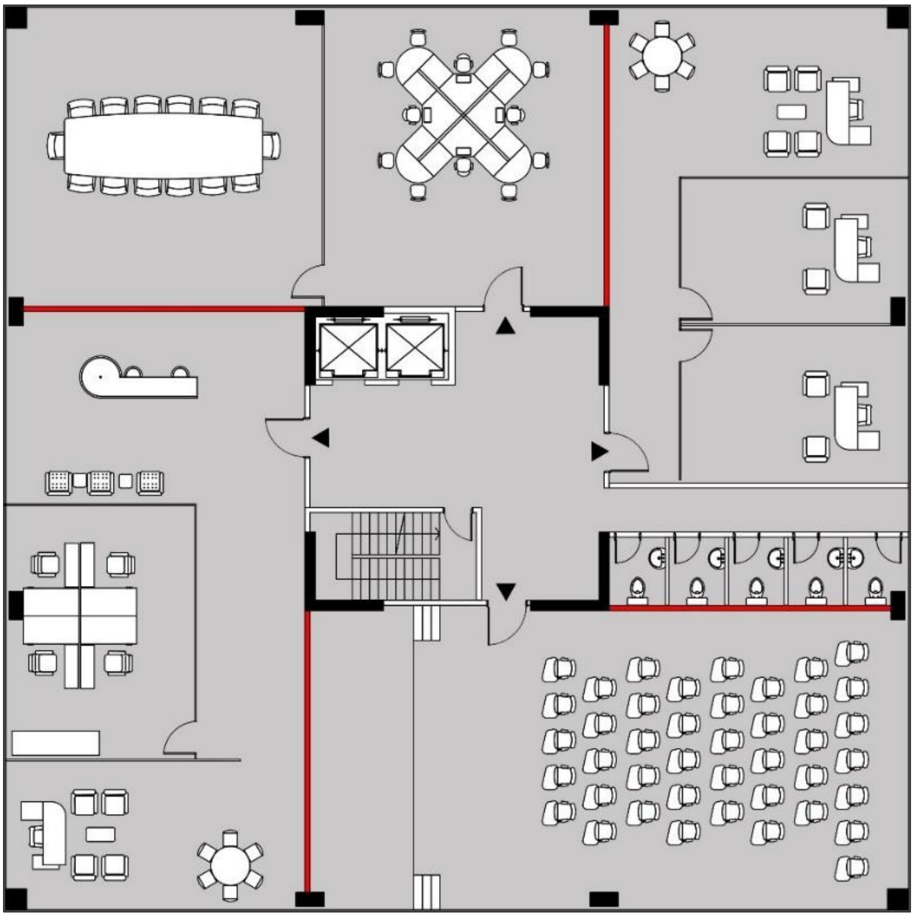


Figure 3.15. Typical floor plan of sample office buildings and each drywall under analyses in red color

Table 3.1. *Details Concerning Architectural Plan*

Building Function	Office
Plan Dimensions	25.2 x 25.2 (in x and y direction)
Span Length	8.4 m
Story Height	4 m
Number of Story	8

Structural Design of Office Buildings

The structural system of generic building models is comprised of reinforced concrete frame elements and shear walls. For modeling and reinforced concrete (RC) member design check, ProtaStructure 2018 software is used since it provides structural designing in accordance with a wide range of regulations including Turkish Earthquake Code (TEC 2007) specifications and Turkish Design and Construction Rules of Reinforced Concrete Structures (TS 500). Therefore, RC member design check is carried out in ProtaStructure 2018.

The sample projects don't have a basement floor and their foundation is assumed a fixed base system based on TEC 2007 by ProtaStructure. Structural model, including eight floors with 4 meters story height, is generated and analyzed to evaluate the superstructure. Columns, beams, shear walls and slabs are easily created by using element tools in the interface of the ProtaStructure. The rigid diaphragm is defined on slab members to distribute the loads uniformly on beam elements. The dead load of the elements is automatically calculated by ProtaStructure. Additionally, super dead load is added as 3,5 kN/m^2 including the weight of the partitions, finishing, *etc*. For the live load, it is specified from Design Loads for Buildings (TS 498) according to the function of the buildings so for the office buildings, live load is arranged as 2 kN/m^2. The seismic parameters adapted from TEC 2007 and TS500 are also added to the analysis to take into consideration seismic effects on the superstructure. The seismic demands of a building depend on the site classification. The location of the case models is İstanbul, Turkey; within the first-degree seismic zone so Response Spectrum points both elastic and design spectrum is acquired from TEC 2007 according to the first-degree seismic zone for the response spectrum analysis. The seismic inputs and requirements from TEC 2007 and TS 500 are applied automatically by ProtaStructure.

Table 3.2. *Design Inputs for Case Models*

Used Material	C30 Concrete
Super Dead Load	3,5 kN/m^2
Live Load (from TS 498)	2 kN/m^2

Table 3.3. *Seismic Inputs for Response Spectrum Analysis adapted from TEC 2007 & TS 500*

Seismic Zone	Zone 1
Ductility Level	High
Importance Factor (I)	1
Soil Class	Z3
Damping	5%

In conformity with the guidelines in TEC 2007 and TS 500, with the help of the easy modeling and well-defined design case in ProtaStructure, RC frame elements design check is performed. According to the analysis results, a design check of RC members is controlled and section sizes of the elements are determined. Two different structural model design is checked in ProtaStructure according to design and maximum credible earthquakes; 475 and 2475 year return periods as mentioned before so it is obtained the same office building with different structural element sizes. In Tables 3.4 and 3.5, different section sizes of the structural elements are shown.

Table 3.4. *Section sizes of the structural elements in the modeled building for 475-year spectrum (units in cm)*

Element	Section	Thickness	Material	Comment
Column	600 x 600		C30	Edge columns
Column	400 x 800		C30	Intermediate columns
Beam	400 x 700		C30	Exterior & Intermediate beams
Beam	400 x 800		C30	Interior beam
Shear Wall	30 x 210		C30	Core walls
Slab		20	C30	

Table 3.5. *Section sizes of the structural elements in the modeled building for 2475-year spectrum (units in cm)*

Element	Section	Thickness	Material	Comment
Column	900 x 900		C35	Edge columns
Column	600 x 1300		C35	Intermediate columns
Beam	400 x 700		C35	Exterior beams
Beam	400 x 800		C35	Intermediate beams
Beam	400 x 900		C35	Interior beam
Shear Wall	30 x 210		C35	Core walls
Slab		20	C35	

Structural design check of the elements is completed so the studying models (Figure 3.16) are ready for modeling and analyzing for the next steps of the study.

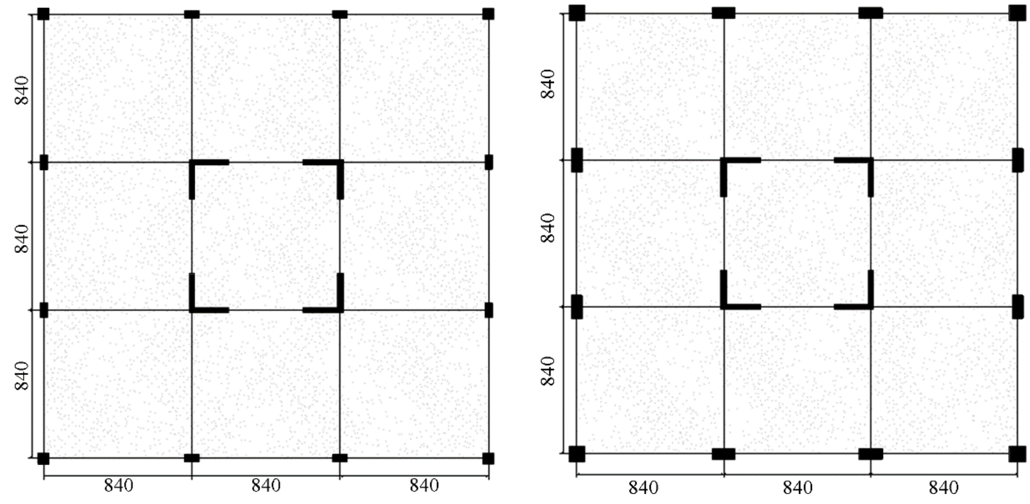


Figure 3.16. Two building models, structurally designed by two different design period spectrums (475-year and 2475-year design spectrum)

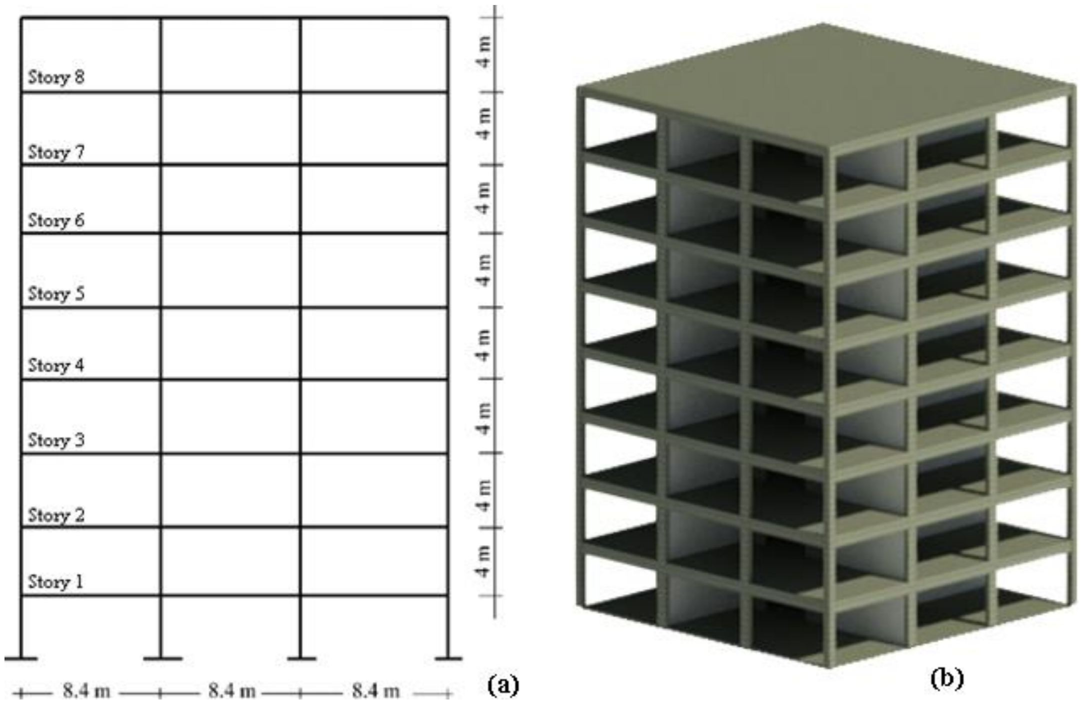


Figure 3.17. (a) In elevation view of case models; (b) Structural Model extracted from the Building Information Model in Autodesk Revit Software

3.2.2. Used Enabler BIM Tools and Add-ins

Building Information Modelling (BIM) Technology is the initiator of this study. The whole process is tried to remain within shared BIM working platform so used tools and applications should be compatible with each other and allow data exchange between them. Selected BIM compatible analysis tools are experienced in the former section in terms of the ability of data exchange, quality of analysis, modeling capability, and ease of user interface. As a result of the former section, Revit is selected as the main modeling platform for each discipline and ETABS is chosen for the structural analysis owing to having advantages like widely-used in the AEC industry, having a user-friendly interface and it's data exchange capability.

In this regard, as a modeling tool, **Autodesk Revit** is preferred due to providing strong communication and exchange data with other analysis tools. Revit enables various working templates for different disciplines and also allows bi-directional integration with a wide range of analysis programs. Thus, case models are formed in Revit software then the elaborated model in the Revit platform is sent to **ETABS**. ETABS is a developed structural analysis tool with linear and nonlinear analysis power. It includes many international design codes and provides a flexible workflow, and increases efficiency. One of the most important advantages of ETABS is compatibility with BIM platforms and still, it is tried to improve sharing data methods. CSI, the production company of ETABS, is developed a plug-in to qualify strong communication with Autodesk Revit. In the data exchange operation, for smooth and successful data flow between Revit Structure and ETABS, a special plug-in **CSiXRevit,** which is a bi-directional data flow plugin for Revit, is created. In the data transition process, transferred elements can be selected by the users so fully control data exchanged can be facilitated by CSiXRevit. To transfer the data, an intermediate data exchange file (.exr) is used. The necessary building elements in the Revit model are sent to ETABS without losses, warnings, and errors by using CSiXRevit. In ETABS, after the importing .exr file, the analysis can run for getting results. Afterward, results in ETABS are exported to **MS Excel** to evaluate and interpret the outputs. In Excel, final calculations and assessments are completed and then results are inserted to Revit interface with the help of an add-in called **IMAGINiT Utilities for Revit**. IMAGINiT provides an integration link between Revit and Excel. Thanks to IMAGINiT, relevant data is matched with the target object because this plug-in links up Revit object through their Revit Element Identity number. IMAGINiT saves time by making many manual steps automatic. It includes a number of tools but in this study, it is enabled from IMAGINiT to exchange data between Excel and Revit. This add-in provides a direct link between Revit and Excel thus data can exchange bi-directionally. The parameters that wanted to import to the Revit model are specified and information about these items is controllably taken to the modeling interface of Revit. Eventually, the outputs turn back to Autodesk Revit, and so bi-directionally data flow loop is completed.

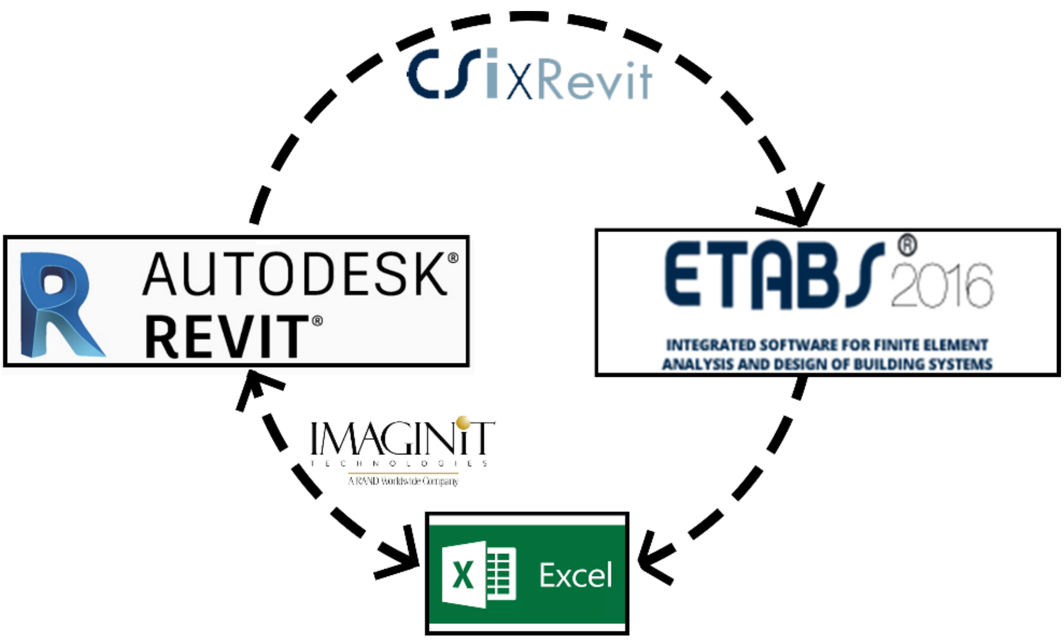


Figure 3.18. Data flow schema used among BIM compatible tools and add-ins

3.2.3. Seismic Parameters for Drywall Design (Limiting Values)

Drywall systems with lightweight steel sub-systems are the focused non-structural components in the scope of this study. The general features and information about drywall systems are explained in the second chapter. Although drywall systems are subjected to fewer earthquake loads rather than solid infill walls due to weight reduction, drywall systems are also damaged during the earthquakes. This threatens the safety of life and property and buildings' resiliency. It is referred to some experimental and analytical studies concerning the seismic behavior of drywall systems in the literature chapter. In this section, the company evaluations and approaches to seismic behavior and design of drywall systems are investigated. Additionally, the limiting criteria for the application of drywall systems are searched before starting mass production.

The seismic design of non-structural systems is still pointed at issue for the industry. The experimental studies are proceeded in the laboratories but examined partial and limited scale experiments cannot develop seismic studies. To produce a more beneficial and usable method for the seismic design of the non-structural elements, an automated and integrative methodology should be proposed. When considered specific to the seismic design of drywall systems, the production companies have some installation standardizations. Almost all partitions in the current studies are produced serially and similarly by firms in accordance with their general application rules. Based on wall height and type, standard wall production is applied with specific stud type and spacing in 30 cm, 40 cm or 60 cm, and typical gypsum boards in standard sizes. In other words, the installation documents of drywall systems, created by production companies, are not dependent upon special wall conditions. In terms of seismicity, firms do not produce special designs and solutions. To obtain more detail and direct information about seismic design and installation studies of drywall systems. technical advisors of two remarkable gypsum board companies which are Knauf and Rigips, were communicated. According to the data taken from technical consultants, the installation standards of lightweight steel stud drywall systems based on studies of the research & development center and also, companies are not interested in calculations and special seismic design of elements. Generally, drywall systems are grouped as interior partitions, walls in wet areas and shaft walls in the projects and then the whole system is produced stereotypically. If the applied projects reach to adequate maturity level in detail, it can be taken precautions and fortifications for holding heavy equipment in the target wall systems but most projects are revised and changed but production companies cannot follow the revisions.

From the point of the technical sources, as classified in ASCE/SEI 41-13 (ASCE, 2013) and mentioned before in the second chapter, lightweight steel stud gypsum boards are both acceleration and deformation sensitive elements so earthquake load can cause in-plane and out-of-plane damage in drywall systems. Due to the attachment of full-height walls to the top and bottom of the structure, deformation and displacement on the structure lead to frame deformation and so the connection of frame and wall surface fails then typical in-plane damage; breaking and cracking appears on the wall planes. This damage case cannot influence the building resiliency severely and it's retrofit studies are not required more time and much money. On the other hand, the earthquake load creates floor acceleration and the acceleration causes the inertial forces. Forces on the walls, rigidly attached to floors, can devastate the connections and result in typical out-of-plane damage. Owing to high acceleration on the walls, incurred losses are the flexural cracking, connection failures and so overturning and completely collapse. Moreover, if heavy items and equipment are anchored to the partitions, they could be more vulnerable to out-of-plane damage. This case damage in partitions interrupts building resiliency and causes money and time losses.

Lightweight partitions are exposed to deformations because of structural connections. In order to protect the walls, there should be a gap between connections of walls and structural elements which helps in-plane movement. Yet, these walls in the out-of-plane movement are restrained (FEMA 356, 2000). Therefore, in this study, to interpret the seismic performance of lightweight steel stud gypsum board partitions, the out-of-plane loading is taken into consideration. To prevent and minimize the out-of-plane damage on the drywall systems, the earthquake resistance must be guaranteed the horizontal force coming at the right angle (90°) to the wall plane direction.

Drywalls should be earthquake resistant, especially in the seismic zones so it is important to design and install them specifically. In 2008, Knauf Gips KG published a book concerning 'Seismic Design and Drywalling'. This book (Henkel *et al.*, 2008) proposed the steps of choosing appropriate drywall sub-structures according to requirements in Figure 3.19.

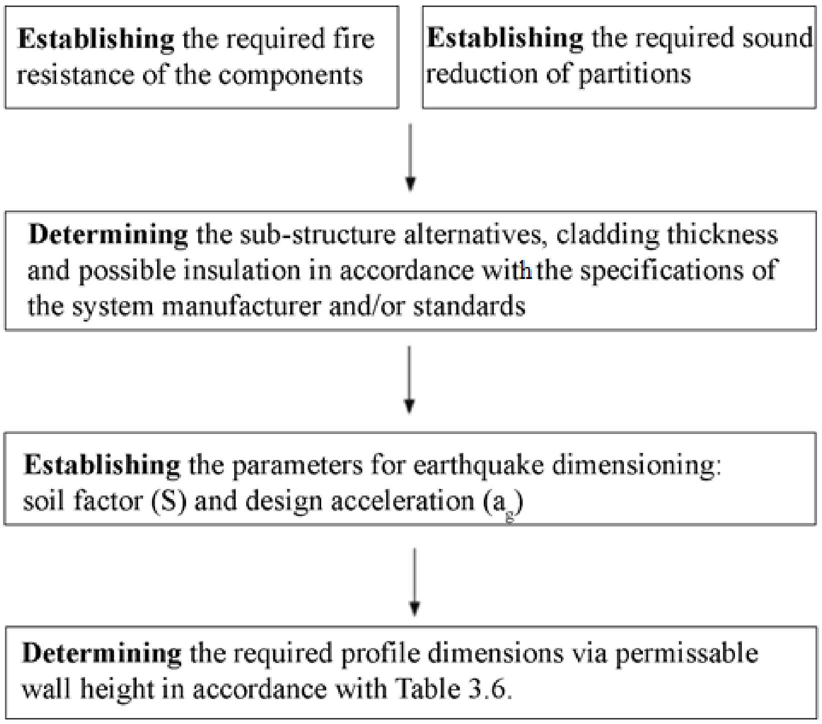


Figure 3.19. Choosing steps for lightweight steel stud partitions (Henkel et al., 2008)

The authors, Henkel, Holl, and Schalk (2008) asserted a generalization including approximate values for applying drywall systems in allowing wall height depending on earthquake loads. In the following table (Table 3.6), according to different earthquake zone and surface conditions, allowable wall heights and metal stud types are categorized in accordance with 60 cm spacing of studs. In preparation for this table, it is referred to Eurocode 8, EN 1998. In the design process of non-load bearing partitions, the soil factor (taken from Eurocode 8) and the design acceleration (related to the earthquake zone) are the only needed figures. Then, the required steel stud profile type in specified spacing is decided according to wall height.

Table 3.6. *The required steel stud profile type concerning wall height in accordance with earthquake load (Taken from Henkel et al., 2008)*

$S \cdot a_g$ [m/s²]	Permissible wall heights in m, spacing of studs 60 cm								
	W111. single metal stud frame, sinlge-layer cladding 1x12.5 mm			W112. single metal stud frame, double-layer cladding 2x12.5 mm			W113. single metal stud frame, triple-layer cladding 3x12.5 mm		
	CW50	CW75	CW100	CW50	CW75	CW100	CW50	CW75	CW100
1.8	2.75	3.75	4.25	3.5	5	5.75	4	5.5	6.5*
2.3								5.25*	6.5**
2.7							3.75	5*	6**
3.2					4.75	5.75*	3.75*	4.5**	5.5**
3.6				3.25	4.5*	5.75**	3.5*	4.25**	5.25**
4.0				3	4.25*	5.5**	3.25*	4**	5**
4.5					4*	5**	3**	3.75**	4.25**
5.0				2.75	3.75*	4.75**		3.5**	4**
5.4							2.75**		3.75**
5.6					3.5*	4.5**			3.5**
6.3				2.5	3.25*	4.25**	2.5**	3**	3.25**
7.2				2.5*	3.25**	4**		2.75**	2.75**

* Reduction of the anchoring distance of the circumferential perimeter runners to 0.75 m

** Reduction of the anchoring distance of the circumferential perimeter runners to 0.50 m

The standard anchoring distance of the circumferential perimeter runners amounts to 1 m.

The capacity of drywall systems against out-of-plane damage risks, based on acceleration value and soil factors, is tabulated with approximate values by Knauf to determine the required profile used for installation according to S (soil type) and a_g (design acceleration value). These approximate capacity values from Knauf is taken as limiting criteria in the comparison with acceleration demand to decide used profile type, anchoring distance in the following parts of this study.

In 2015, Knauf Group developed seismic studies of lightweight steel stud drywalls incorporation with the University of Naples "Federico II" to provide missing points in this subject so new book was published in the name of ''Lightweight steel drywall constructions for seismic areas; Design, research and applications'' (Fiorino et al, 2015). Differently from the first book, controlling parameters of the seismic behavior of lightweight steel stud gypsum board partitions are also related to weight and attachment conditions of the walls in addition to the acceleration and height factor mentioned in the first book. In this regard, the acceleration sensitive elements are designed for lateral seismic forces that are related to elements' weight and acceleration. The design forces applied to the components are evaluated in the light of two international standards; European code and American codes. The American codes become prominent in the calculation of horizontal design seismic force for this study since Turkish standards are produced via originating from American standards. Chapter 13 of ASCE/ SEI 7-10 (ASCE, 2010) includes seismic demands on nonstructural components. In Chapter 13, horizontal seismic design forces on walls applied to the center of the components, are determined by the following equation (Equation-1). In this research, accelerations used for seismic force are determined by linear dynamic analysis methods, therefore, seismic force values are determined by Equation-1:

$$F_p = \frac{a_i \, a_p \, W_p}{\left(\frac{R_p}{I_p}\right)} A_x$$

F_p = seismic design force

a_i = maximum acceleration at level i obtained from the modal analysis

a_p = component amplification factor (taken from table of ASCE/ SEI 7-10)

W_p = component operating weight

R_p = component response modification factor (taken from table of ASCE/ SEI 7-10)

I_p = component Importance Factor (taken from table of ASCE/ SEI 7-10)

A_x = the torsional amplification factor (taken from ASCE/ SEI 7-10)

To calculate the seismic design forces for each drywall in the projects, the required data in these equations are maximum accelerations from analysis (a_i) and weight of walls (W_p). The remaining inputs in the equation are constant values taken from tables of ASCE/ SEI 7-10. The maximum acceleration values for each wall are inserted into the Revit model by BIM compatible tools. In Revit, the operating weight of the wall is obtained correctly. Thanks to the building model in Revit, the equipment on the walls become clear from the pre-design stage of the projects so the seismic design forces of lightweight partitions can be calculated in Revit.

In addition to acceleration and force value for the seismic design of lightweight partitions, due to being deformation-sensitive elements, drift ratios of walls should be regulated before the application of walls. Excessive drift ratio can cause structural and non-structural damage thus the specifications restrict the drift ratio of elements (FEMA 454, 2006). In ASCE and IBC, the computed drift ratio is limited between 0.02 and 0.01. In TEC 2019 also includes a restriction about drift ratio. In Section 4.9.1.3 of TEC 2019, an equation is defined based on maximum story drift, floor height, constant value and vibration period of building. Drift ratios associated with building performance levels for lightweight partitions are taken from ASCE/SEI 4-13

(2013). Lastly, these reference values from ASCE/SEI 4-13 (2013) and maximum drift ratio values from time history analysis are evaluated for three case models.

3.3. Methodology

In this section of the study, the process of setting numerical studies for seismic demand of drywalls by using BIM compatible tools is indicated. The main aim of the numerical studies is to show that the seismic demand of each drywall is different so the standardized application of drywalls in the buildings cannot be effectual in terms of seismic resiliency. To illustrate the differences in the seismic demand and so differences of required implementation criteria, three cases are defined according to various seismicity levels. In the BIM compatible analysis tools, seismic input and requirements are added to the models. Then, the analyses are run and outputs are shared with all stakeholders via sending results to the main coordinated building model in Revit. This process schematically exhibited in the flow chart section of the methodology.

3.3.1. Numerical Analysis for Seismic Demand of Drywalls in BIM Tools

The seismic demand of steel stud gypsum board interior partition walls is developed numerically in this section. The two generic building models created in the first-degree seismic zone in İstanbul, Turkey are studied. To follow drift ratios and to obtain seismic acceleration on the drywalls in the out-of-plane direction, linear time history analysis is performed by using ETABS software. For the dynamic time history analysis procedures, seven real ground motion records for İstanbul which are design and maximum credible earthquakes; compatible with 475 and 2475 year spectrum, are selected respectively. Also, to show how drywalls in the generic buildings behave in different content ground motion, three different cases are defined in Table 3.7.

The case models are produced in Autodesk Revit and it is sent to ETABS via using CSiXRevit plug-in so the structural models are automatically obtained to perform for analyses. In Revit, the building information model is generated in a coordinated manner with all disciplines so the required data is easily drawn from the intelligent model. The exchanging elements are sent to ETABS with their Revit Element Id numbers so after the analysis completed, outputs about target objects turn back to the main building model in the light of element id numbers.

Table 3.7. *Defined Three Different Cases*

	Structurally design spectrums	**Recorded ground motion content used in time history analysis**
Case I	Designed by 475-year return period	Return period of 475-year
Case II	Designed by 475-year return period	Return period of 2475-year
Case III	Designed by 2475-year return period	Return period of 2475-year

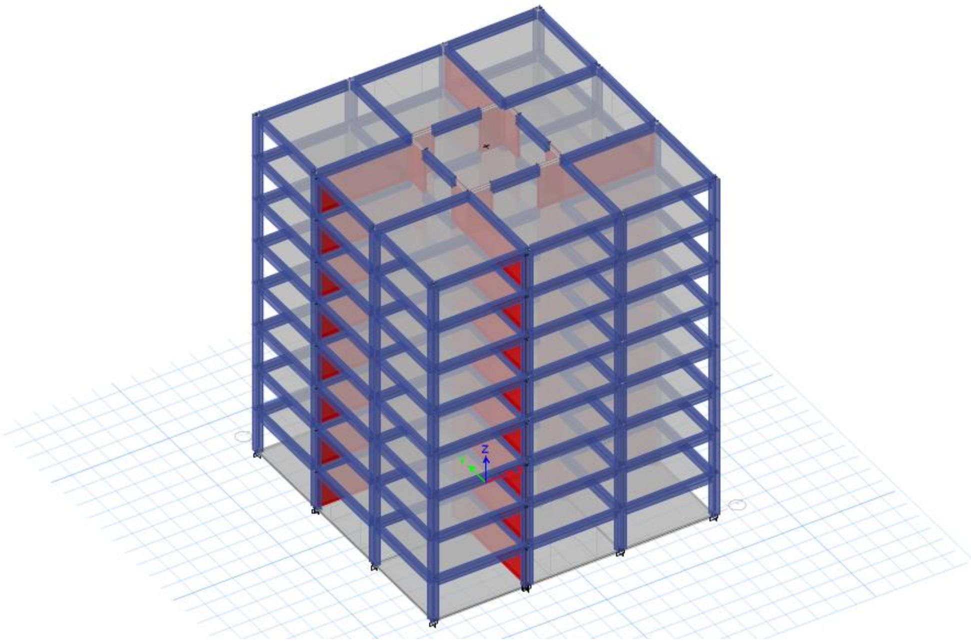


Figure 3.20. The 3-dimensional structural model in ETABS taken from Autodesk Revit modeling via using CSiXRevit plug-in

For this study, the RC structural system elements and drywalls should be extracted to ETABS from Revit. Based on one of the main objectives of this study, the success of data sharing about the seismic acceleration and drift ratio of all drywalls is investigated. Therefore, in the studying model, drywall elements should exist. However, CSiXRevit plug-in only works for transferring of structural elements between Revit and ETABS. Hence, for importing drywall data to structural analysis software, partition elements are signed as structural components in the Revit model and so partitions and structural elements are send to ETABS. In order to neutralize partitions in the analysis, their property/stiffness modifiers for analysis, material weight and mass, mechanical properties of the material are ignored. In this way, drywalls in the structural model are used as guideline elements for their locations.

In the case models, before running analyses, the parameters should be revised in accordance with TS500 and TEC 2007. In the point of load cases, super dead load (3.5 kN/m^2- calculated approximate value) and live load for office buildings (2 kN/m^2 – taken from TS498, Design Loads for Buildings) are added to slabs. The rigid diaphragms are defined on each floor slabs. According to TEC 2007, the stiffness modifiers are applied into relevant members which are columns, beams and shear walls. For columns and shear walls, the flexural modifiers are taken 0.80 and for beams, 0.40 is used. Afterward, for running analysis, time history function is defined by uploading selected ground motion records for X and Y directions. Lastly, a linear modal history analysis case is set. The focused drywalls in the three case models are called Wall X1, Wall X2, Wall Y1, and Wall Y2. The length of the drywalls is 805 cm and their height is 320-330 cm which is connected to structural elements from both sides as seen in Figure 3.21. In line with this study, out-of-plane behavior of drywalls is investigated hence to observe the out-of-plane behavior of Wall X1 and Wall X2, the ground motion acceleration is applied in the Y direction and for the Wall Y1 and Wall Y2, the ground motion acceleration is applied in the X direction.

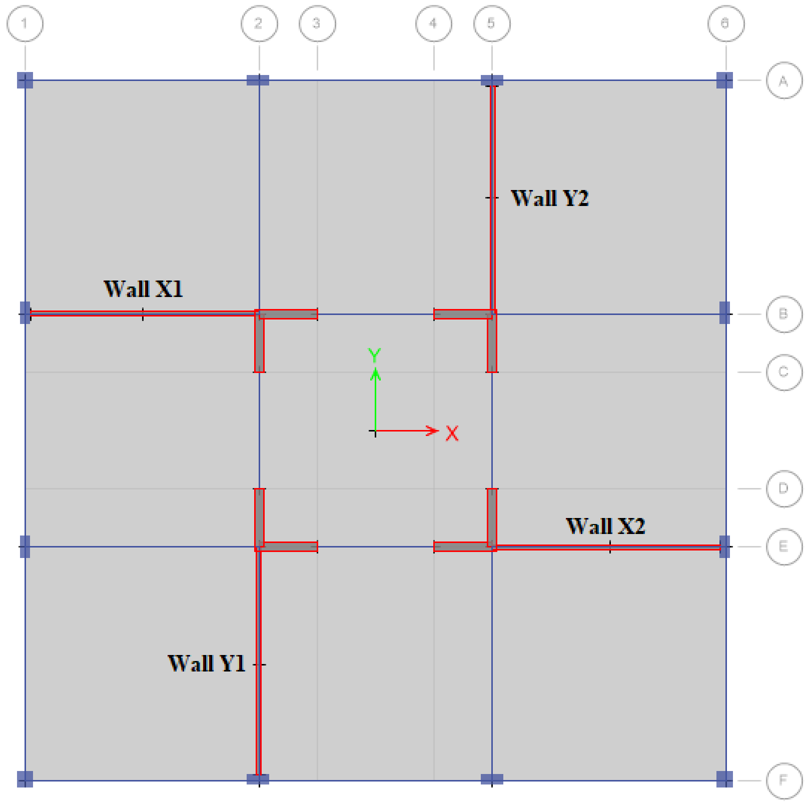


Figure 3.21. Each drywall under analyses (Wall X1, Wall X2, Wall Y1 & Wall Y2) in the case model plan in the interface of ETABS

For three cases, the same adjustments in ETABS as mentioned above are applied and the obtained seismic demands from various case results are compared with the seismic capacity of the walls. In three different cases, it is wanted to illustrate that each steel stud gypsum board partitions need to design individually according to their specifications. Also, the installation of these systems should be unique instead of mass-production.

3.3.2. Flow chart of the Study

At the beginning of the study, the generic building models are structurally designed in ProtaStructure 2018 based on TEC 2007 and TS 500 (Figure 3.22). Two different generic models are checked in accordance with 475-year and 2475-year response spectrum. ProtaStructure is an effective BIM collaboration tool. To share and synchronize data among different disciplines between Autodesk Revit and ProtaStructure, ProtaBIM is developed. When ProtaBIM is downloaded, an add-in tab is seen in the Revit interface and so ProtaBIM provides the bi-directional link for easy round-tripping. This direct link works smoothly in the data exchange process from ProtaStructure to Revit but direct integration link does not work directly away, yet. Therefore, the ProtaStucture process presently cannot join BIM flow until Prota develops the strong connection link from Autodesk Revit to ProtaStructure. ProtaStructure is a promising BIM compatible tool for collaboration and integration among structural disciplines and others.

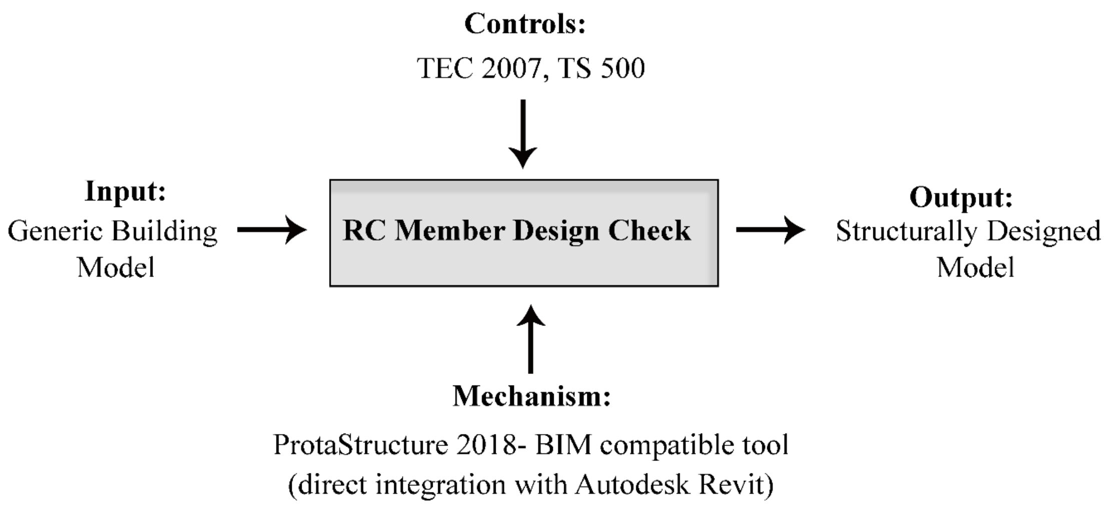


Figure 3.22. IDEF0 diagram illustrating the RC member design check of the generic case models

The structurally designed case models are modeled in Autodesk Revit for creating intelligent building information models. The following process of this research is data sending to ETABS via using CSXiRevit. Then, in ETABS, analyses are carried out and the analysis results are exported to excel to compare the limiting values. Finally, the results are sent to back the Revit to share with all team members from Excel by way of IMAGINiT. The whole process is demonstrated in Figure 3.23 step by step.

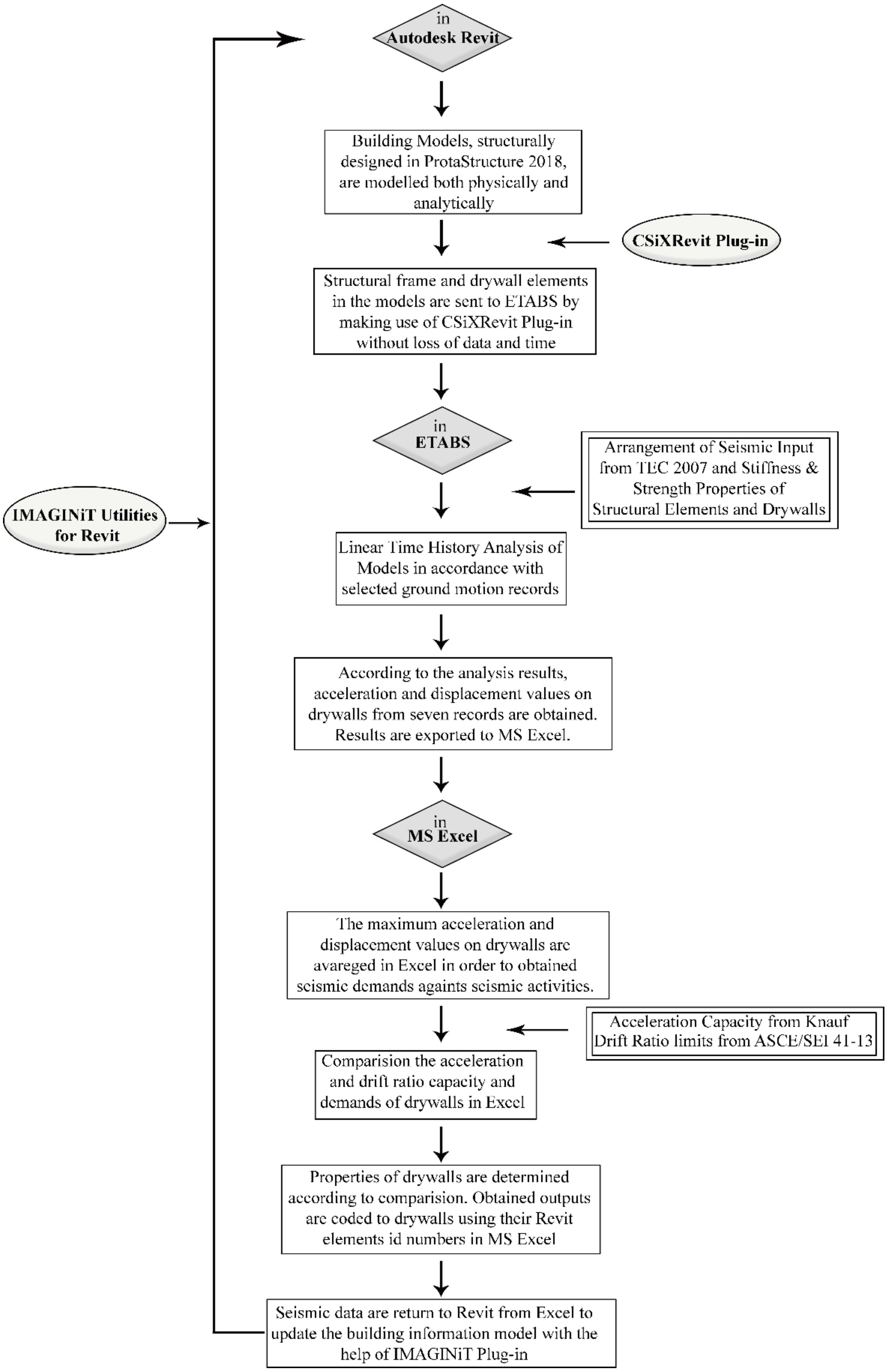


Figure 3.23. Methodological process of the research

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, the results of time history analysis; acceleration & displacement demands of drywalls for three cases are demonstrated. In each case, peak accelerations and maximum drift ratios of drywalls are shown for each ground motion. For the assessments of the results, analysis outputs are exported from structural analysis tools, ETABS to Microsoft Excel. In Excel, the seismic demands and seismic capacity of drywalls are compared and the inferences from comparisons are associated with Revit elements id numbers. Afterward, the outputs in Excel is sent back to the main building model in Revit through IMAGINiT add-ins. The functioning of the proposed framework by using BIM Technology for this research is checked. Finally, the effectiveness of using Building Information Modelling Technology in the seismic design of drywalls is evaluated.

4.1. Time / Response History Analysis Results

The numerical research is conducted to make a comparison of seismic demand and capacity of drywall elements. Partitions are both acceleration and deformation sensitive elements according to Section 13.6.2 of STANDARD ASCE/SEI 41-13 (2013) hence to decide the application of these elements against seismic activities, peak acceleration value and maximum drift ratio of walls are investigated. In the typical floor plan, focused partitions are named Wall X1, Wall X2, Wall Y1, Wall Y2 as shown in Figure 4.1. In the scope of this research, out-of-plane acceleration and displacement of walls are taken into consideration therefore for Wall X1 and X2, the effect of ground motion acceleration applied in the Y direction is observed and similarly, for Wall Y1 and Y2, the effect of ground motion acceleration applied in the X direction is discovered. For the analysis results, Wall X1 and Wall Y1 are exhibited as sample elements as the Wall X1 behaves similarly with Wall X2 and the Wall Y1 behaves similarly with Wall Y2.

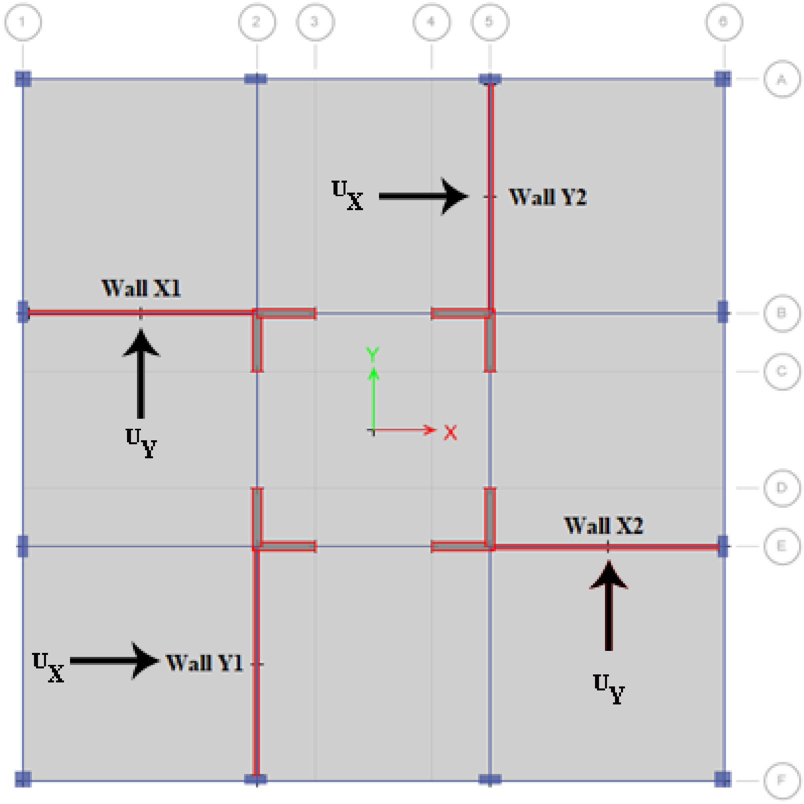


Figure 4.1. Focused walls and their response components (UX and UY)

For the analysis models, structural elements and metal stud gypsum board walls are extracted to ETABS from the Autodesk Revit building model. The data transformation process saves time by automatizing manual works thanks to BIM compatible tools. The data in the Revit building model is exported in .exr file format by using CSiXRevit plug-in and then .exr file data is imported to ETABS. In this way, analysis models are automatically and smoothly transferred into ETABS software. One of the most important features of the data flow process is that when the data is exchanged among Autodesk Revit and ETABS, elements are coded according to their Revit element id numbers and analysis results are synchronized with these numbers. Thus, the outputs of the analyses can systematically return to the coordinated Revit building model. Thus, the method catalyzes the bi-directionally data exchange within BIM concept.

In ETABS, linear dynamic analyses are carried out to obtain peak acceleration and drift ratio of drywalls. For the analyses, in total 14 ground motion records are used. Seven ground motion records compatible with 475-year return period spectrum and the remaining seven ground motion records compatible with 2475-year return period and these records are scaled based on the code based target spectrum. Then the scaled ground motion accelerations are applied to the case models in X and Y directions simultaneously. In this study, the effect of the vertical component of the ground motion is ignored. In the studying models, joints are defined on each floor level in the middle of the walls to measure joint acceleration and joint displacement. According to the analysis results of each ground motion time series, recorded acceleration value and displacements of joints are obtained. For each wall under analysis on each floor level, the absolute average value of top and bottom joints on the walls are found throughout time series then the maximum value is specified as the wall acceleration for one of the records (Figure 4.2). This operation is repeated for seven times for each ground motion records. Finally, the analysis is completed by averaging the peak accelerations from seven records for partition walls.

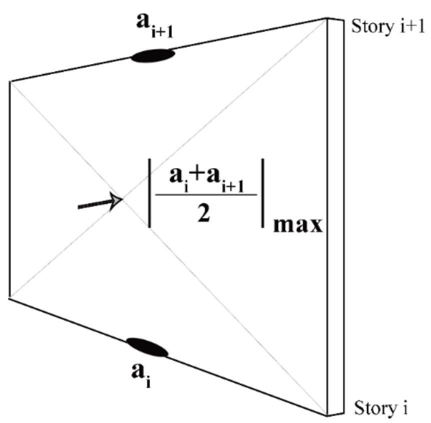


Figure 4.2. Out-of-plane wall acceleration for each ground motion record

In seismic design, the difference of deflection at the top and bottom of the story is called inter-story drift. Thus, the drift ratio of the wall is defined as the ratio of deflection inter-story to story height. This ratio is multiplied with 100 to obtain the percentage of inter-story drift ratio (Figure 4.3). Consequently, to see the seismic performance level of walls, the drift ratio of walls on each floor is calculated for seven records and averaged.

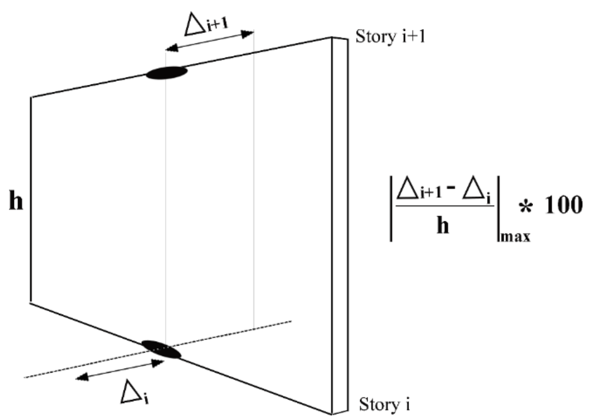


Figure 4.3. Drift ratio (%) of walls for each ground motion record

The study intends to illustrate with three different cases that the seismic demands in terms of acceleration and drift ratio of each drywall element in the projects are different conversely what is applied in the AEC industry currently. As indicated before, the implementation of drywall systems is generalized in a few groups for all projects but the required application precautions differ from what is supposed and accepted. These differentiations are shown with the analysis results of case studies.

4.1.1. Seismic Demands for Case I

For the analysis of Case I where the seismic design of the structure is based on the design earthquake (for 475-year return period), modal analysis and time history analysis for 7 ground motion records compatible with 10% in 50-year ground motion spectrum are performed in ETABS. According to modal analysis results, the first fundamental mode of the system is translation in the x-direction, the second mode is translation in the y-direction and the third mode is torsional. The analysis resulted in a period (T) of 1.632 sec in both directions.

Peak Acceleration Values of Drywalls

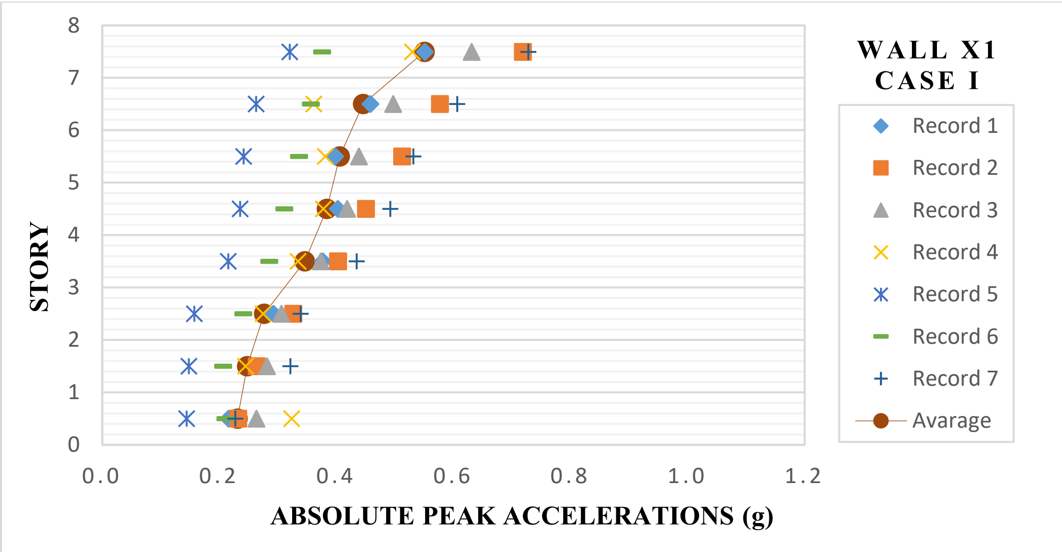
In this section, the acceleration time series are obtained by proceeding linear dynamic time history analysis. According to the response history analysis results, the absolute maximum acceleration data for each wall is written down for 7 ground motion (GM) records and the average of each wall under analysis on each floor level are shown in the following tables.

Table 4.1. *Summary of Absolute Peak Accelerations of Wall X1 from 7 GM Records in the y-direction (above) and Absolute Peak Accelerations of Wall Y1 from 7 GM Records in the x-direction (below) for Case I*

WALL X1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.55	0.46	0.40	0.40	0.38	0.29	0.27	0.22
GM Record 2	0.72	0.58	0.51	0.45	0.40	0.33	0.26	0.23
GM Record 3	0.63	0.50	0.44	0.42	0.37	0.31	0.28	0.26
GM Record 4	0.53	0.36	0.38	0.38	0.33	0.27	0.24	0.32
GM Record 5	0.32	0.26	0.24	0.24	0.22	0.16	0.15	0.14
GM Record 6	0.38	0.36	0.34	0.31	0.29	0.24	0.21	0.21
GM Record 7	0.73	0.61	0.53	0.49	0.43	0.34	0.32	0.23
Average (g)	**0.55**	**0.45**	**0.41**	**0.38**	**0.35**	**0.28**	**0.25**	**0.23**

WALL Y1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.60	0.49	0.44	0.38	0.30	0.26	0.24	0.23
GM Record 2	0.79	0.68	0.56	0.47	0.37	0.28	0.18	0.25
GM Record 3	0.54	0.43	0.38	0.31	0.25	0.22	0.23	0.23
GM Record 4	1.01	0.77	0.76	0.73	0.62	0.59	0.49	0.41
GM Record 5	0.24	0.20	0.19	0.21	0.20	0.18	0.16	0.16
GM Record 6	0.28	0.25	0.22	0.21	0.18	0.14	0.10	0.11
GM Record 7	0.50	0.39	0.43	0.48	0.45	0.45	0.38	0.30
Average (g)	**0.57**	**0.46**	**0.43**	**0.40**	**0.34**	**0.30**	**0.25**	**0.24**

The peak acceleration values for Wall X1 and Wall Y1 on each floor for seven records are revealed in detail. In the following figures (Figure 4.4 & 4.5) show that the alteration of absolute peak acceleration values based on any floor levels.



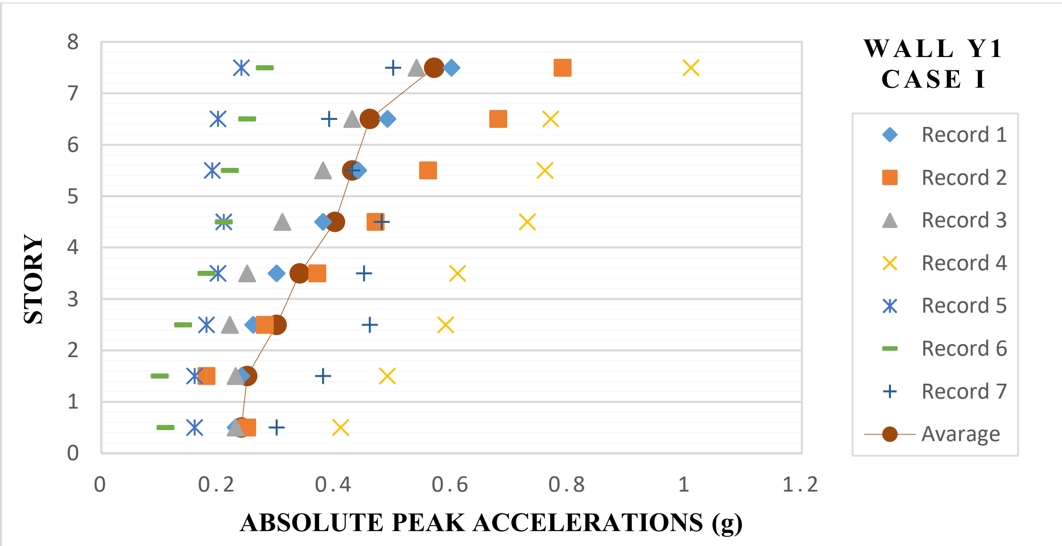


Figure 4.4. Absolute Peak Accelerations of Wall X1 in the y-direction (above) & Absolute Peak Accelerations of Wall Y1 in the x-direction (below)

The final results are displayed schematically in Figure 4.4 and 4.5 that the peak accelerations of drywalls increase towards upper stories. Moreover, the acceleration value of the Wall X1 on the 8th floor is 2.40 times more than the acceleration value of the Wall X1 on the 1st floor. Similarly, for Wall Y1, the acceleration value multiples 2.38 times from the 1st floor to the 8th floor. Consequently, the seismic demands of walls in a project are not the same so the design and application of these elements should be assessed specific to the element itself.

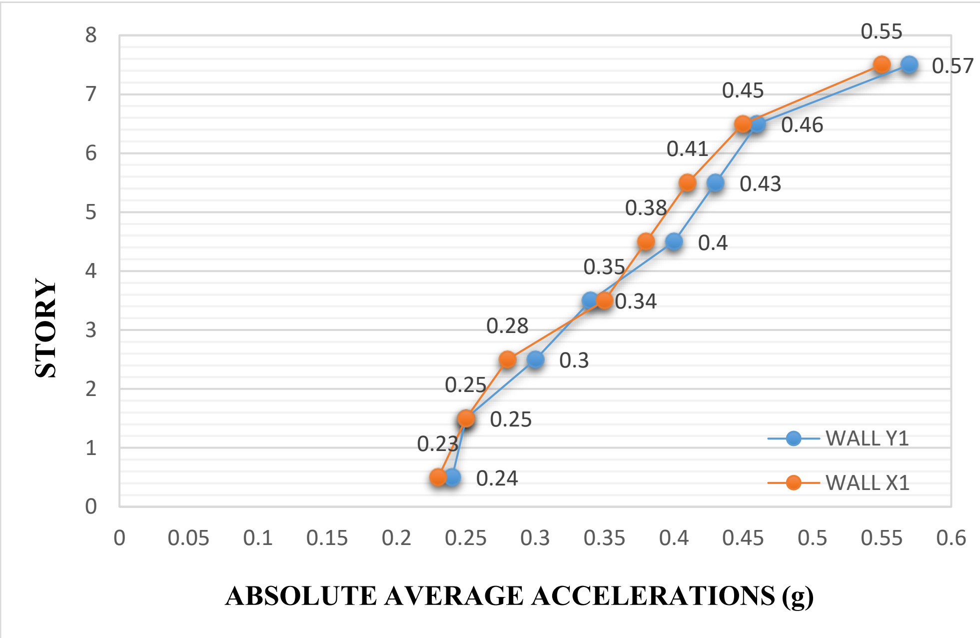


Figure 4.5. Summary of Average Peak Accelerations of Wall X1 & Wall Y1 in different floor levels for Case I

Maximum Drift Ratio (%) of Drywalls

Drywalls are deformation sensitive elements (STANDARD ASCE/SEI 41-13) so the design of deformation sensitive elements should be correlated with inter-story drifts. Therefore, displacement time series obtained by proceeding linear dynamic time history analysis is investigated. Maximum joint displacements are gained by using scaled seven ground motion (GM) records and the maximum drift ratios of drywalls are calculated and listed for drywalls in each floor as seen in Table 4.2.

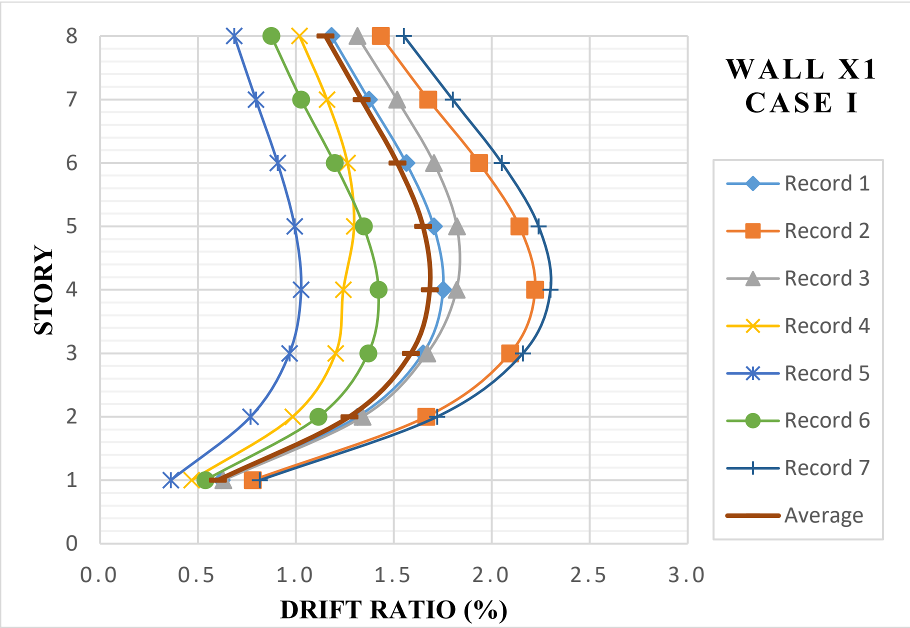
Table 4.2. *Maximum drift ratio(%) of Wall X1 with main direction y (above) & Maximum drift ratio(%) of Wall Y1 with main direction x (below) for Case I*

WALL X1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	1.18	1.37	1.56	1.70	1.75	1.65	1.31	0.62
GM Record 2	1.43	1.68	1.93	2.14	2.22	2.09	1.66	0.78
GM Record 3	1.31	1.52	1.70	1.82	1.82	1.67	1.34	0.63
GM Record 4	1.02	1.16	1.26	1.30	1.24	1.20	0.98	0.47
GM Record 5	0.68	0.79	0.91	0.99	1.03	0.97	0.77	0.36
GM Record 6	0.87	1.03	1.20	1.35	1.42	1.37	1.11	0.54
GM Record 7	1.55	1.80	2.05	2.24	2.30	2.16	1.72	0.82
Average(%)	**1.15**	**1.33**	**1.52**	**1.65**	**1.68**	**1.59**	**1.27**	**0.60**

WALL Y1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	1.28	1.48	1.69	1.84	1.89	1.78	1.41	0.66
GM Record 2	1.73	2.01	2.31	2.52	2.59	2.41	1.90	0.89
GM Record 3	1.07	1.22	1.35	1.44	1.44	1.31	1.01	0.46
GM Record 4	1.92	2.19	2.47	2.73	2.90	2.80	2.26	1.06
GM Record 5	0.48	0.57	0.66	0.72	0.75	0.70	0.56	0.27
GM Record 6	0.63	0.74	0.85	0.94	0.98	0.93	0.74	0.35
GM Record 7	0.88	1.03	1.18	1.28	1.35	1.29	1.04	0.50
Average(%)	**1.14**	**1.32**	**1.50**	**1.64**	**1.70**	**1.60**	**1.28**	**0.60**

The variation of drift ratio for drywalls through building height is investigated separately for seven ground motion records. Then the average value of maximum ratios of all record results is calculated. The results are graphically shown in Figure 4.6.

As seen in Table 4.2 and Figure 4.6, the maximum drift ratios of the Case I model range between 0.60% and 1.70%. In other words, ensuring the safety of the drywalls and the connections against the out-of-plane movement in any seismic activity requires that the anchor movements should be installed properly for the displacements.



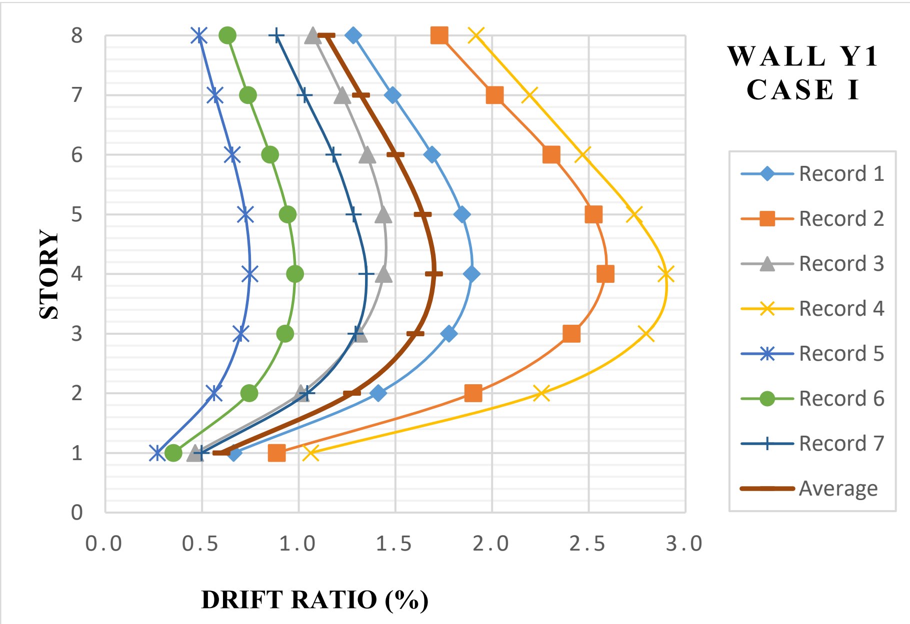


Figure 4.6. Maximum drift ratios of Wall X1 in y-direction (above) & Maximum drift ratios of Wall Y1 in x-direction (below)

4.1.2. Seismic Demands for Case II

For the analysis of Case II which is structurally designed by 475-year return period, it is performed time history analysis for seven ground motion records compatible with 2475-year spectrum in ETABS. The structural system of this case is the same with the Case I, therefore, the modes of the systems and the period is the same with Case model I. Differently from Case I, for time history analysis, seven scaled ground motion acceleration records compatible with 2475-year spectrum are used.

Peak Acceleration Values of Drywalls

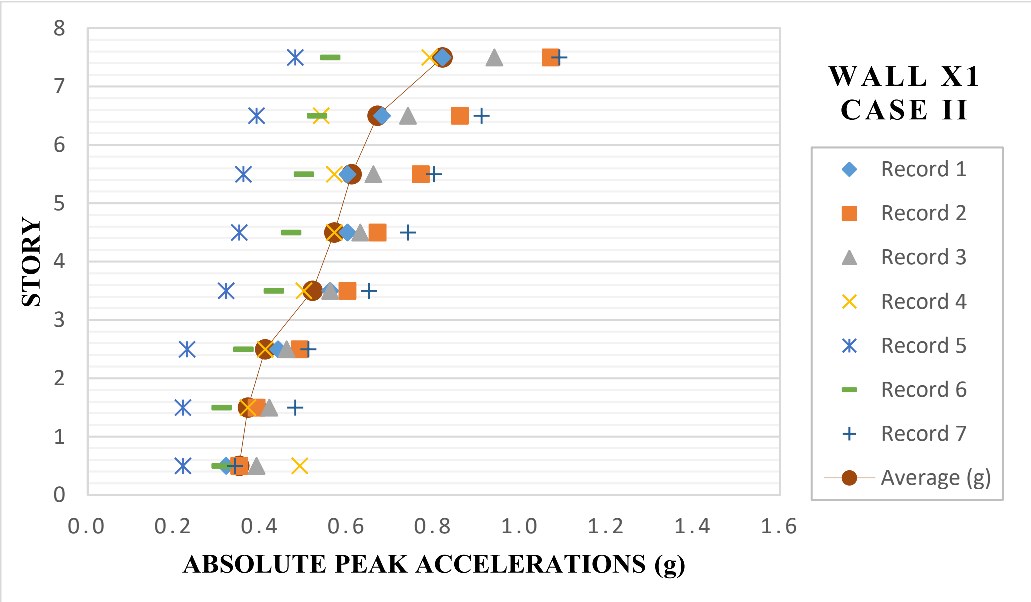
In this section, the acceleration time series obtained by performing linear dynamic time history analyses. According to the time history analysis results, absolute maximum acceleration data for each wall is found for seven ground motion (GM) records and average on focused walls on each floor level are given in Table 4.3.

Table 4.3. *Summary of Absolute Peak Accelerations of Wall X1 from 7 GM Records in the y-direction (above) & Absolute Peak Accelerations of Wall Y1 from 7 GM Records in the x-direction (below) for Case II*

WALL X1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.82	0.68	0.60	0.60	0.56	0.44	0.40	0.32
GM Record 2	1.07	0.86	0.77	0.67	0.60	0.49	0.39	0.35
GM Record 3	0.94	0.74	0.66	0.63	0.56	0.46	0.42	0.39
GM Record 4	0.79	0.54	0.57	0.57	0.50	0.41	0.37	0.49
GM Record 5	0.48	0.39	0.36	0.35	0.32	0.23	0.22	0.22
GM Record 6	0.56	0.53	0.50	0.47	0.43	0.36	0.31	0.31
GM Record 7	1.09	0.91	0.80	0.74	0.65	0.51	0.48	0.34
Average (g)	**0.82**	**0.67**	**0.61**	**0.57**	**0.52**	**0.41**	**0.37**	**0.35**

WALL Y1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.90	0.74	0.66	0.56	0.45	0.39	0.36	0.34
GM Record 2	1.18	1.02	0.84	0.70	0.56	0.42	0.27	0.38
GM Record 3	0.81	0.64	0.56	0.46	0.37	0.33	0.34	0.35
GM Record 4	1.52	1.16	1.14	1.09	0.92	0.88	0.74	0.62
GM Record 5	0.35	0.30	0.28	0.31	0.30	0.27	0.25	0.24
GM Record 6	0.43	0.38	0.33	0.31	0.27	0.21	0.15	0.17
GM Record 7	0.75	0.58	0.65	0.72	0.67	0.68	0.57	0.46
Average (g)	**0.85**	**0.69**	**0.64**	**0.59**	**0.51**	**0.45**	**0.38**	**0.37**

Figure 4.7 shows the alteration of absolute peak acceleration values throughout the building height for each GM records graphically. Figure 4.8 compares averaged absolute peak acceleration values for two orthogonal directions of the building.



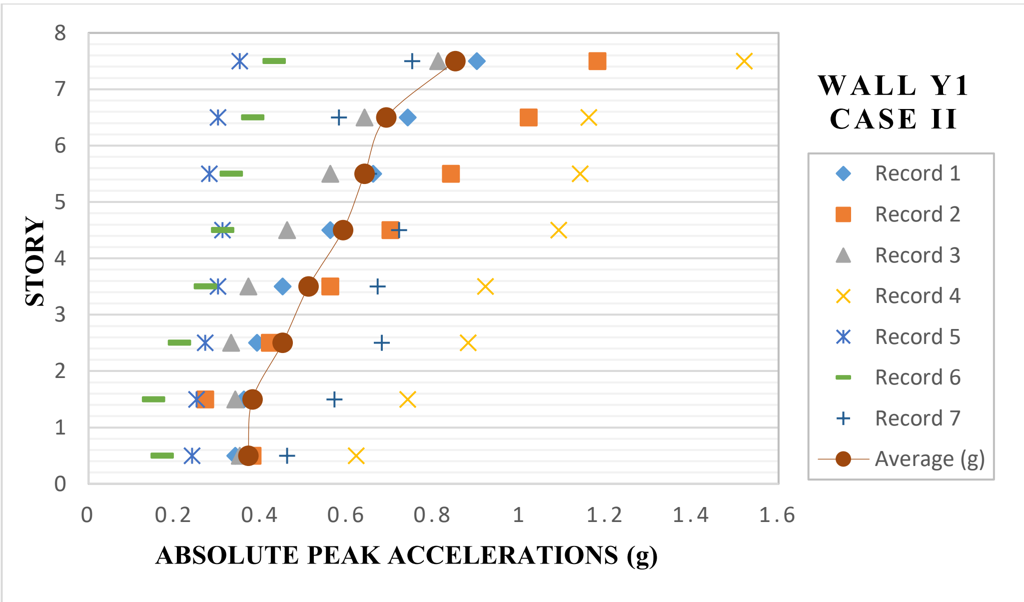


Figure 4.7. Absolute Peak Accelerations of Wall X1 in the y-direction (above) & Absolute Peak Accelerations of Wall Y1 in the x-direction (below)

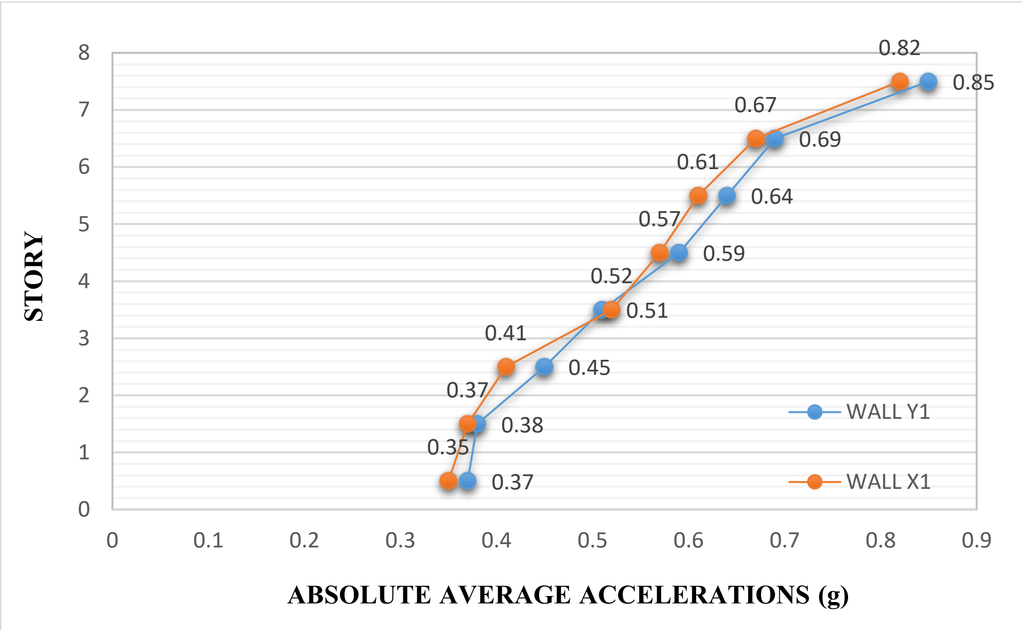


Figure 4.8. Summary of Average Peak Accelerations of Wall X1 & Wall Y1 in different floor levels for Case II

The final results displayed schematically in Figure 4.7 and 4.8 reveal the fact that the peak accelerations of drywalls increase the positions of the walls increase. For instance, the acceleration value of the Wall X1 on the 8th floor is 2.34 times more than the acceleration value of the Wall X1 on the 1st floor. In a similar manner, for Wall Y1, the acceleration value increases 2.30 times from the 1st floor to the 8th floor. Hence for the seismic design of acceleration sensitive drywall partitions, the peak wall acceleration demands should be evaluated for design and implementation.

Maximum Drift Ratio (%) for Drywalls

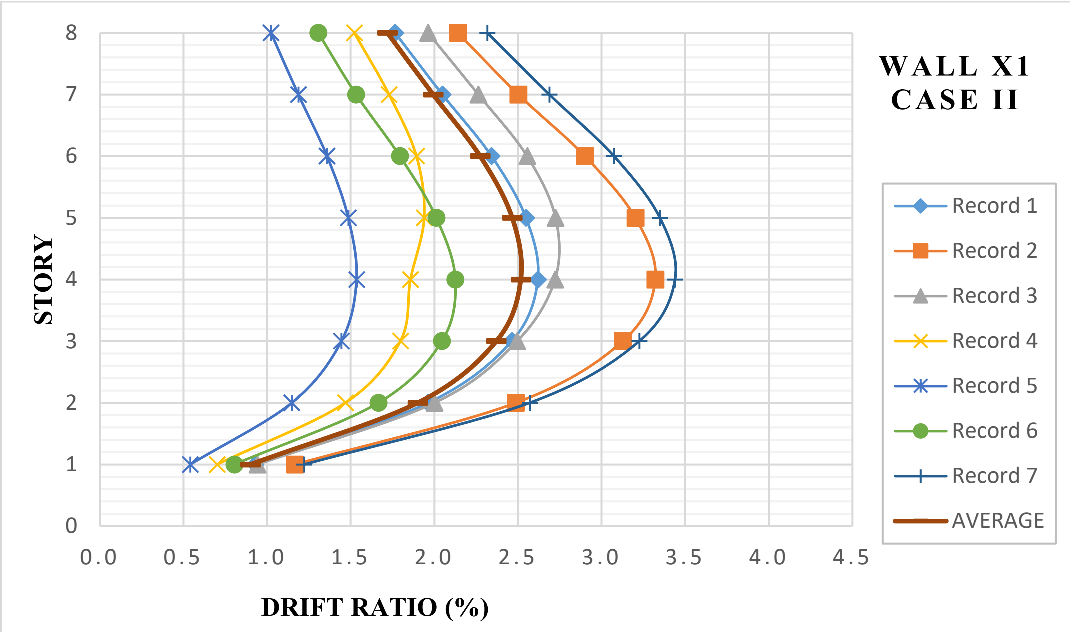
For the seismic design of deformation sensitive elements, it is beneficial to have estimated drift ratios before the application of walls for reliable seismic design since the lateral movements of elements are limited by drift ratios of the elements. Therefore, displacement time series are obtained by proceeding linear dynamic time history analysis. Maximum joint displacements are gained by using scaled seven ground motion (GM) records and the maximum drift ratios of drywalls are calculated for drywalls in each floor as given in Table 4.4.

Table 4.4. *Maximum drift ratio(%) of Wall X1 with main direction y (above) & Maximum drift ratio(%) of Wall Y1 with main direction x (below) for Case II*

WALL X1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	1.77	2.05	2.34	2.55	2.62	2.46	1.96	0.93
GM Record 2	2.14	2.50	2.90	3.20	3.32	3.13	2.49	1.17
GM Record 3	1.96	2.26	2.56	2.72	2.72	2.50	2.00	0.94
GM Record 4	1.52	1.73	1.89	1.94	1.86	1.80	1.47	0.70
GM Record 5	1.02	1.19	1.36	1.49	1.53	1.44	1.15	0.54
GM Record 6	1.31	1.53	1.79	2.01	2.13	2.05	1.67	0.80
GM Record 7	2.32	2.69	3.07	3.35	3.44	3.23	2.57	1.22
Average(%)	**1.72**	**1.99**	**2.27**	**2.47**	**2.52**	**2.37**	**1.90**	**0.90**

WALL Y1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	1.92	2.23	2.53	2.76	2.83	2.67	2.12	0.99
GM Record 2	2.59	3.02	3.46	3.77	3.87	3.62	2.85	1.33
GM Record 3	1.61	1.84	2.03	2.15	2.15	1.97	1.52	0.70
GM Record 4	2.87	3.29	3.70	4.09	4.33	4.19	3.38	1.59
GM Record 5	0.73	0.85	0.98	1.08	1.12	1.05	0.84	0.40
GM Record 6	0.95	1.11	1.28	1.41	1.47	1.39	1.12	0.53
GM Record 7	1.33	1.55	1.77	1.92	2.02	1.94	1.56	0.75
Average(%)	**1.71**	**1.98**	**2.25**	**2.45**	**2.54**	**2.40**	**1.91**	**0.90**

The gained data from seven GM records about the drift ratio of drywalls on each floor is listed separately. The maximum drift ratios of drywalls in each story are averaged. The results are graphically illustrated in Figure 4.9.



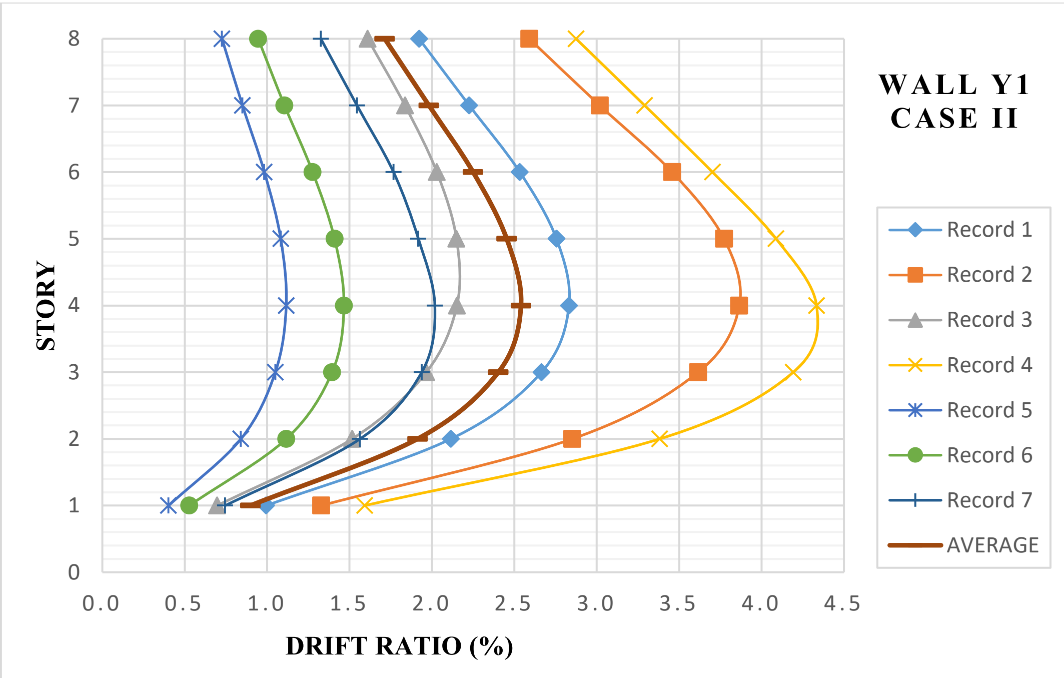


Figure 4.9. Maximum drift ratios of Wall X1 in the y-direction (above) & Maximum drift ratios of Wall Y1 in the x-direction (below)

As seen from the tables and figures, the maximum drift ratios of the Case II model range between 0.90% and 2.54%. Therefore, in the design and installation process of drywalls, the differences in the drift ratio of drywalls should be taken into consideration for seismic safety.

4.1.3. Seismic Demands for Case III

In Case III, the seismic design of the structure is for ground motion with 2475-year return period. Time history analyses of this structure for seven GM records compatible maximum credible earthquake spectrum is performed in ETABS. Modal analysis of the structure showed that the first fundamental mode of the system is translation in the x-direction, the second mode is translation in the y-direction and the third mode is torsional. Due to the symmetry, period (T) of the structure in both principal directions is found as 1.295 sec.

Peak Acceleration Values of Drywalls

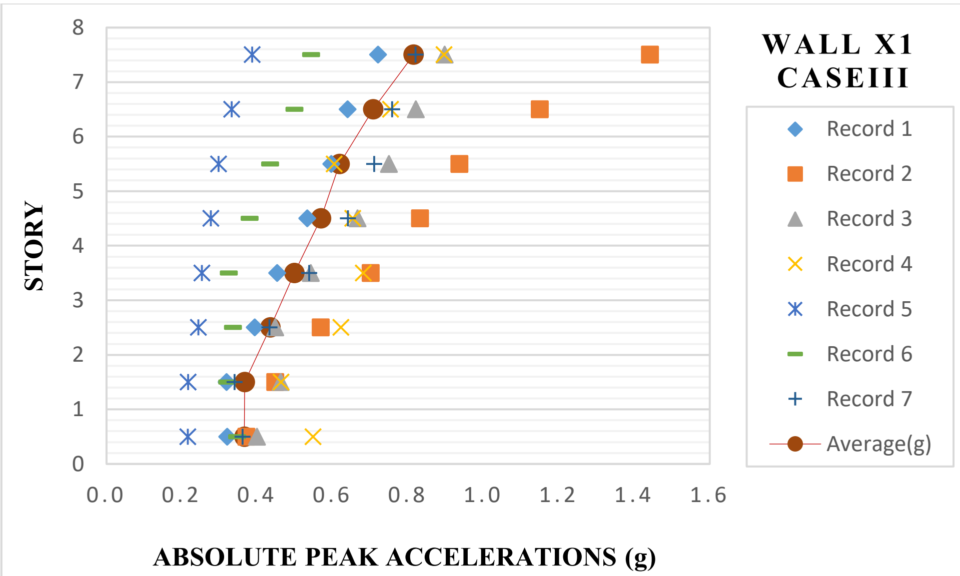
Linear dynamic time history analyses are performed. Absolute peak acceleration values of walls per story and their average is given in Tables 4.5.

Table 4.5. *Summary of Absolute Peak Accelerations of Wall X1 from 7 GM Records in the y-direction (above) & Absolute Peak Accelerations of Wall Y1 from 7 GM Records in the x-direction (below) for Case III*

WALL X1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.72	0.64	0.60	0.53	0.45	0.39	0.32	0.32
GM Record 2	1.44	1.15	0.94	0.83	0.70	0.57	0.45	0.37
GM Record 3	0.90	0.82	0.75	0.67	0.54	0.45	0.46	0.40
GM Record 4	0.89	0.75	0.60	0.65	0.68	0.62	0.46	0.55
GM Record 5	0.39	0.33	0.30	0.28	0.25	0.24	0.22	0.21
GM Record 6	0.54	0.50	0.43	0.38	0.32	0.34	0.32	0.35
GM Record 7	0.82	0.76	0.71	0.64	0.54	0.43	0.34	0.36
Average (g)	**0.81**	**0.71**	**0.62**	**0.57**	**0.50**	**0.43**	**0.37**	**0.37**

WALL Y1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.77	0.66	0.67	0.66	0.56	0.48	0.39	0.33
GM Record 2	1.12	0.98	0.89	0.80	0.66	0.53	0.36	0.40
GM Record 3	1.07	0.92	0.76	0.59	0.51	0.49	0.44	0.36
GM Record 4	1.44	1.25	1.14	0.97	0.76	0.71	0.72	0.65
GM Record 5	0.15	0.12	0.10	0.11	0.11	0.13	0.11	0.21
GM Record 6	0.41	0.37	0.32	0.28	0.22	0.19	0.18	0.18
GM Record 7	0.92	0.68	0.73	0.76	0.69	0.65	0.61	0.44
Average (g)	**0.84**	**0.71**	**0.66**	**0.60**	**0.50**	**0.45**	**0.40**	**0.37**

Figure 4.10 shows the variation of absolute peak acceleration values for each story whereas Figure 4.11 displays the comparison of average absolute peak acceleration of each story in X and Y directions.



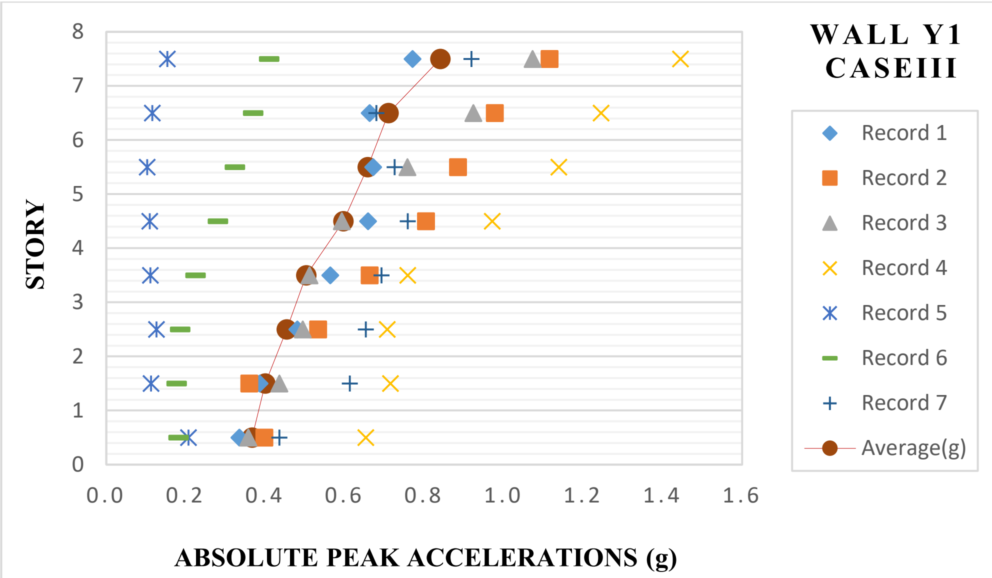


Figure 4.10. Absolute Peak Accelerations of Wall X1 in the y-direction (above) & Absolute Peak Accelerations of Wall Y1 in the x-direction (below)

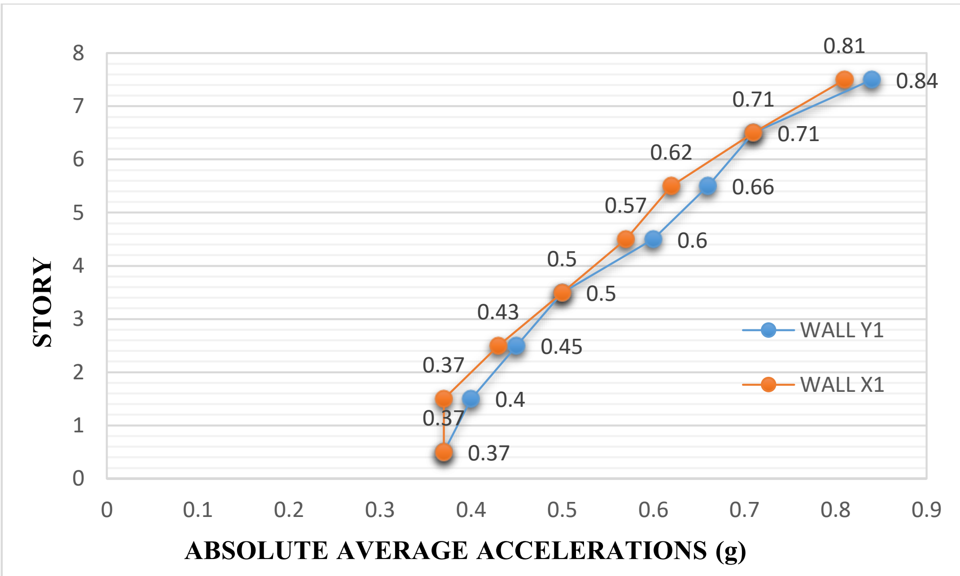


Figure 4.11. Summary of Average Peak Accelerations of Wall X1 & Wall Y1 in different floor levels for Case III

The results are similar to those of Case I and Case II. The variation in wall accelerations necessitates the design and application of drywall systems by considering the changing demands on walls depending on the wall location.

Maximum Drift Ratio (%) for Drywalls

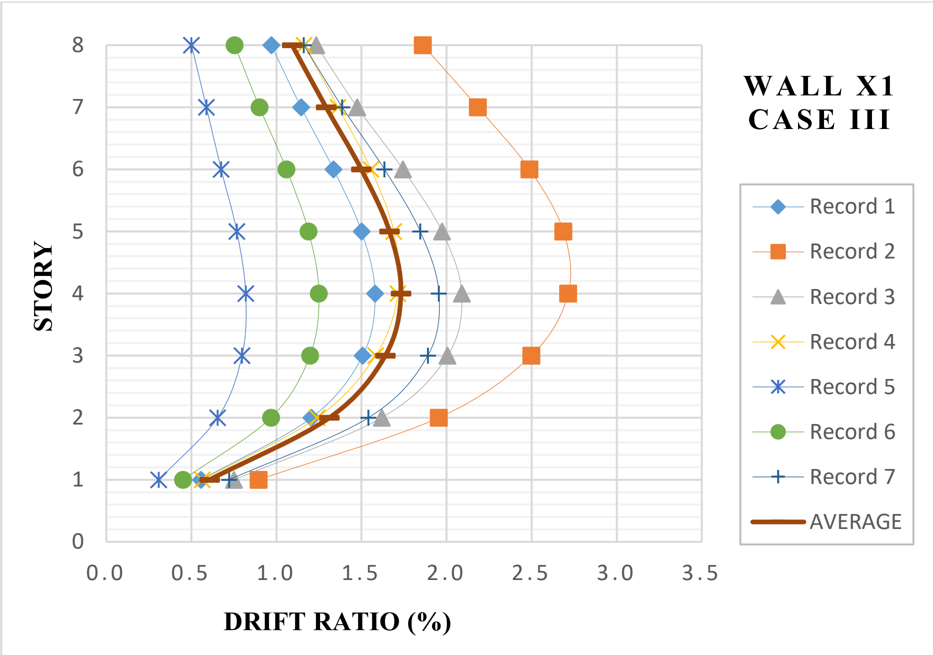
Similar to Case I and Case II, in Case III modal, the maximum drift ratio of drywalls in each floor are obtained for seven GM records through linear dynamic time history analyses. The drift ratios of drywalls are calculated by making use of data from the displacement time series. The maximum drift ratios of walls are listed in Table 4.6.

Table 4.6. *Maximum drift ratio(%) of Wall X1 with main direction y (above) & Maximum drift ratio(%) of Wall Y1 with main direction x (below) for Case III*

WALL X1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	0.97	1.14	1.34	1.50	1.58	1.51	1.21	0.56
GM Record 2	1.86	2.18	2.49	2.69	2.71	2.50	1.95	0.90
GM Record 3	1.23	1.48	1.74	1.97	2.09	2.01	1.62	0.75
GM Record 4	1.16	1.36	1.56	1.69	1.71	1.58	1.24	0.56
GM Record 5	0.50	0.59	0.67	0.77	0.82	0.80	0.65	0.31
GM Record 6	0.75	0.90	1.06	1.19	1.25	1.20	1.97	0.45
GM Record 7	1.16	1.39	1.64	1.85	1.96	1.89	1.54	0.72
Average(%)	**1.09**	**1.29**	**1.50**	**1.66**	**1.73**	**1.64**	**1.31**	**0.61**

WALL Y1	Story 8	Story 7	Story 6	Story 5	Story 4	Story 3	Story 2	Story 1
GM Record 1	1.03	1.20	1.40	1.59	1.71	1.67	1.36	0.64
GM Record 2	1.52	1.80	2.09	2.33	2.47	2.38	1.93	0.90
GM Record 3	1.44	1.71	1.98	2.18	2.25	2.11	1.66	0.76
GM Record 4	1.94	2.29	2.65	2.93	3.04	2.87	2.28	1.05
GM Record 5	0.19	0.22	0.25	0.26	0.26	0.24	0.19	0.09
GM Record 6	0.57	0.68	0.79	0.88	0.92	0.87	0.70	0.32
GM Record 7	1.14	1.33	1.48	1.56	1.65	1.64	1.36	0.64
Average(%)	**1.12**	**1.32**	**1.52**	**1.68**	**1.76**	**1.68**	**1.35**	**0.63**

The average values of maximum drift ratios of drywalls are calculated. The results are graphically shown in Figure 4.12.



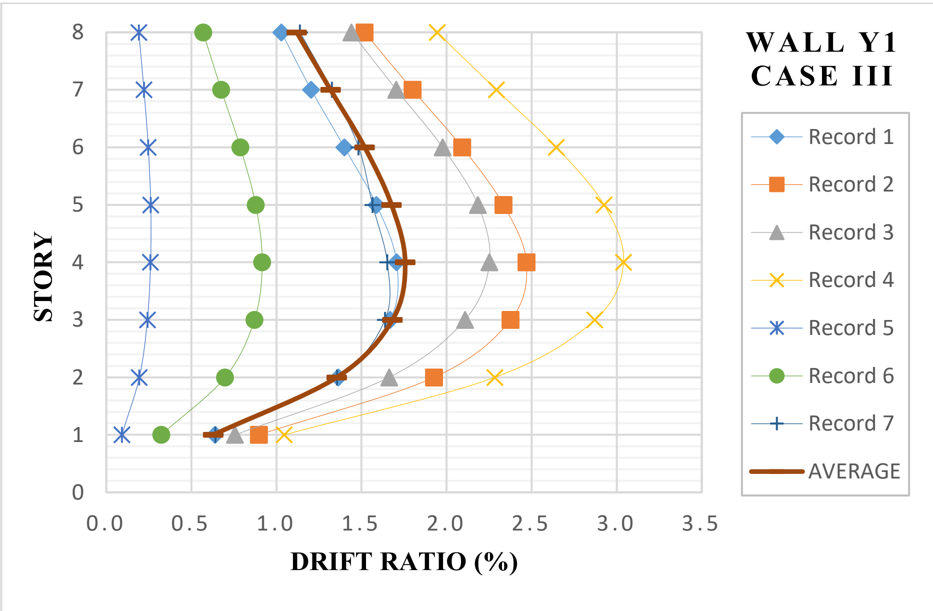


Figure 4.12. Maximum drift ratios of Wall X1 in the y-direction (above) & Maximum drift ratios of Wall Y1 in the x-direction (below)

As seen from Table 4.6 and Figure 4.12, the maximum drift ratios of the Case III range between approximately 0.60% and 1.75%. Differences in drift ratios of drywalls for three cases refer to different performance levels of drywalls during the earthquake. Thus, in the design and installation process, drift ratios of drywalls should be evaluated properly in terms of target building performance levels.

4.2. Comparison of Demands and Capacity of Drywalls

The out-of-plane failure mechanism of drywall partitions is either acceleration or displacement-based, therefore, peak accelerations and maximum drift ratios of steel stud gypsum board partitions are obtained by making use of from linear dynamic time history analyses. These results are compared with the empirical capacity values, and the performances of the elements are assessed.

4.2.1. Acceleration Demands vs. Capacity of Drywall Partitions

Drywalls should be designed considering earthquake loadings. According to performance-based seismic design philosophy, the serviceability and maintenance of the building should not be influenced by the damage of any building element. In 2008, Henkel, Holl & Schalk carried out a study about seismic design and drywalling. As outputs of this study, the authors put forward a summary data regarding the seismic design of walls in terms of design accelerations. According to acceleration demands on walls, permissible wall heights are prescribed for the given wall types, the usable profile types, and anchoring distances. The values given in Table 4.7 (Henkel *et al.*, 2008) are used in this study for demand and capacity comparisons.

Table 4.7. *Allowable steel stud gypsum wall height with 60 cm stud spacing (Henkel et al., 2008)*

<table>
<tr><th rowspan="4">S. a_g (g)</th><th colspan="9">Permissible wall heights in m, spacing of studs 60 cm</th></tr>
<tr><th colspan="3">W111 wall type</th><th colspan="3">W112 wall type</th><th colspan="3">W113 wall type</th></tr>
<tr><td colspan="3">Single metal stud frame, single layer cladding (1x 12.5 mm)</td><td colspan="3">Single metal stud frame, double layer cladding (2x 12.5 mm)</td><td colspan="3">Single metal stud frame, triple layer cladding (3x 12.5 mm)</td></tr>
<tr><th>CW50</th><th>CW75</th><th>CW100</th><th>CW50</th><th>CW75</th><th>CW100</th><th>CW50</th><th>CW75</th><th>CW100</th></tr>
<tr><th>0.18</th><td rowspan="12">2.75</td><td rowspan="12">3.75</td><td rowspan="12">4.25</td><td rowspan="4">3.5</td><td rowspan="3">5</td><td rowspan="3">5.75</td><td rowspan="2">4</td><td>5.5</td><td>6.5*</td></tr>
<tr><th>0.23</th><td>5.25*</td><td>6.5**</td></tr>
<tr><th>0.28</th><td>3.75</td><td>5*</td><td>6**</td></tr>
<tr><th>0.33</th><td>4.75</td><td>5.75*</td><td>3.75*</td><td>4.5**</td><td>5.5**</td></tr>
<tr><th>0.37</th><td>3.25</td><td>4.5*</td><td>5.75**</td><td>3.5*</td><td>4.25**</td><td>5.25**</td></tr>
<tr><th>0.41</th><td rowspan="2">3</td><td>4.25*</td><td>5.5**</td><td>3.25*</td><td>4**</td><td>5**</td></tr>
<tr><th>0.46</th><td>4*</td><td>5**</td><td rowspan="2">3**</td><td>3.75**</td><td>4.25**</td></tr>
<tr><th>0.51</th><td rowspan="3">2.75</td><td rowspan="2">3.75*</td><td rowspan="2">4.75**</td><td rowspan="3">2.75**</td><td>4**</td></tr>
<tr><th>0.55</th><td rowspan="2">2.75**</td><td>3.75**</td></tr>
<tr><th>0.57</th><td>3.5*</td><td>4.5**</td><td>3.5**</td></tr>
<tr><th>0.64</th><td>2.5</td><td>3.25*</td><td>4.25**</td><td rowspan="2">2.5**</td><td rowspan="2">2.5**</td><td>3.25**</td></tr>
<tr><th>0.73</th><td>2.5*</td><td>3.25**</td><td>4**</td><td>2.75**</td></tr>
<tr><td colspan="10">* Reduction of the anchoring distance of the circumferential perimeter runners to 0.75 m</td></tr>
<tr><td colspan="10">** Reduction of the anchoring distance of the circumferential perimeter runners to 0.50 m</td></tr>
<tr><td colspan="10">The standard anchoring distance of the circumferential perimeter runners amounts to 1 m.</td></tr>
</table>

For the Case I & II models, the height of the partitions in the project is 3.3 m and in Case III, wall heights are 3.2m. Steel stud partitions used for all cases are chosen as double-layer gypsum boards (W112 wall type) with single metal steel stud. In accordance with the comparisons, the profile type and anchoring distance for each wall are either specified if it is available or identified as critical. Then, the results are associated with the elements id number and tabularized in Excel for defined three cases (Table 4.8; Table 4.9; Table 4.10, respectively).

Table 4.8. *Evaluation of the peak acceleration values of Wall X1(above) & Evaluation of the peak acceleration values of Wall Y1 in Case I based on Table 4.7*

CASE I WALLX1	**Element ID Number**	**Peak Accelerations (g)**	**Wall Type**	**Profile Type**	**Anchoring Distance (m)**
Story 8	453305	0.55	W112	CW75	0.75
Story 7	452859	0.45	W112	CW75	0.75
Story 6	452327	0.41	W112	CW75	0.75
Story 5	452214	0.38	W112	CW75	0.75
Story 4	451224	0.35	W112	CW75	0.75
Story 3	450981	0.28	W112	CW50	1
Story 2	450394	0.25	W112	CW50	1
Story 1	449797	0.23	W112	CW50	1
The height of all partitions is 3.30 m. in the project					

CASE I WALLY1	**Element ID Number**	**Peak Accelerations (g)**	**Wall Type**	**Profile Type**	**Anchoring Distance (m)**
Story 8	453667	0.57	W112	CW75	0.75
Story 7	453212	0.46	W112	CW75	0.75
Story 6	452769	0.43	W112	CW75	0.75
Story 5	451878	0.40	W112	CW75	0.75
Story 4	451714	0.34	W112	CW75	0.75
Story 3	450841	0.30	W112	CW50	1
Story 2	450505	0.25	W112	CW50	1
Story 1	450011	0.24	W112	CW50	1
The height of all partitions is 3.30 m. in the project					

Table 4.9. *Evaluation of the peak acceleration values of Wall X1(above) & Evaluation of the peak acceleration values of Wall Y1(below) in Case II based on Table 4.7*

CASEII WALX1	**Element ID Number**	**Peak Accelerations (g)**	**Wall Type**	**Profile Type**	**Anchoring Distance (m)**	**Warnings**
Story 8	453305	0.82	W112			**Critical**
Story 7	452859	0.67	W112	CW100	0.50	
Story 6	452327	0.61	W112	CW75	0.50	
Story 5	452214	0.57	W112	CW75	0.75	
Story 4	451224	0.52	W112	CW75	0.75	
Story 3	450981	0.41	W112	CW75	0.75	
Story 2	450394	0.37	W112	CW75	0.75	
Story 1	459797	0.35	W112	CW75	0.75	
The height of all partitions is 3.30 m. in the project						

CASEII WALY1	**Element ID Number**	**Peak Accelerations (g)**	**Wall Type**	**Profile Type**	**Anchoring Distance (m)**	**Warnings**
Story 8	453667	0.85	W112			**Critical**
Story 7	453212	0.69	W112	CW100	0.50	
Story 6	452769	0.64	W112	CW100	0.50	
Story 5	451878	0.59	W112	CW100	0.50	
Story 4	451714	0.51	W112	CW75	0.75	
Story 3	450841	0.45	W112	CW75	0.75	
Story 2	450505	0.38	W112	CW75	0.75	
Story 1	450011	0.37	W112	CW75	0.75	
The height of all partitions is 3.30 m. in the project						

Table 4.10. *Evaluation of the peak acceleration values of Wall X1(above) & Evaluation of the peak acceleration values of Wall Y1 (below) in Case III based on Table 4.7*

CASEIII WALLX1	**Element ID Number**	**Peak Accelerations (g)**	**Wall Type**	**Profile Type**	**Anchoring Distance(m)**	**Warnings**
Story 8	451965	0.81	W112			Critical
Story 7	451464	0.71	W112	CW75	0.50	
Story 6	451360	0.62	W112	CW75	0.50	
Story 5	450493	0.57	W112	CW75	0.75	
Story 4	449956	0.50	W112	CW75	0.75	
Story 3	449691	0.43	W112	CW75	0.75	
Story 2	449541	0.37	W112	CW50	1	
Story 1	448963	0.37	W112	CW50	1	
The height of all partitions is 3.20 m. in the project						

CASEIII WALLY1	**Element ID Number**	**Peak Accelerations (g)**	**Wall Type**	**Profile Type**	**Anchoring Distance (m)**	**Warnings**
Story 8	452324	0.84	W112			Critical
Story 7	451837	0.71	W112	CW75	0.50	
Story 6	451021	0.66	W112	CW75	0.50	
Story 5	450931	0.60	W112	CW75	0.75	
Story 4	450304	0.50	W112	CW75	0.75	
Story 3	449694	0.45	W112	CW75	0.75	
Story 2	449544	0.40	W112	CW75	0.75	
Story 1	449401	0.37	W112	CW50	1	
The height of all partitions is 3.20 m. in the project						

4.2.2. Drift Ratio Demands vs. Capacity of Drywall Partitions

The vertical structural frame elements deflect under lateral loading and this causes different displacement at the top and bottom of the stories. In seismic design, story drift effects both the in-plane and out-of-plane the behavior of partitions which are attached to the structure. Thus, for a given performance level of the structure, the limiting values of drift ratios are specified by codes for both structural and non-structural elements. For different element types, limiting drift ratios are specified in the codes. For lightweight partitions, the limiting values are taken from ASCE/SEI 41-

13 (ASCE, 2013) and so damage limit states are specified for seismic design. The permitted limits depend on types of non-structural elements and limited drifts prevent possible damage (FEMA 454, 2006). In ASCE/SEI 41-13 (ASCE, 2013), the non-structural performance levels of light partitions are separated into three groups; Life Safety, Position Retention, and Operational (Table 4.11).

Table 4.11. *Limited drift ratios for building performance levels (ASCE/SEI 41-13)*

Building Performance Levels for Light Partitions	
Operational	The drift ratio computed in accordance with Section 13.6.2 of ASCE 41-13 shall be limited to **0.01 (1 %)**
Position Retention	The drift ratio computed in accordance with Section 13.6.2 of ASCE 41-13 shall be limited to **0.02 (2 %)**
Life Safety	Nonstructural light partitions need not be evaluated for the Life Safety Nonstructural Performance Level.

For the operational building performance level, the drift ratio of lightweight steel stud gypsum board partitions is limited to 1%. Up to 1% drift ratio means drywall elements can resume their function after the earthquake. For the position retention performance level, drywall elements are damaged and cannot maintain their function, but they are safe in the place where the drift ratio is between 1% and 2%. If drift ratio exceeds 2%, drywalls are damaged and broken off their position, yet according to the codes, this damage does not risk to life safety. Although life safety performance minimizes the risks related to the drywalls, at this level, the drywalls are not functional and repairable. When the issue is considered from the point of reinforced concrete structural elements, the Turkish Earthquake Code (TEC, 2007) limits the maximum drift ratio with 2%. In other words, if the drift ratio exceeds 2%, moderate damage is inevitable for RC structures where falling and serious damage are observed in lightweight partitions. In this study, the drift ratios and performance levels of the steel stud gypsum boards in three case models are evaluated via comparing drift ratios from time history analysis results and limited drift ratios from ASCE/SEI 41-13 (see table 4.11). The outputs are given in Tables 4.12-4.14 for steel stud gypsum board walls associating with the elements id number.

Table 4.12. *The performance levels of Wall X1 (above) and Wall Y1(below) according to the average of maximum drift ratio values from seven ground motion records for Case I*

CASE I WALL X1	**Element ID Number**	**Drift Ratio (%)**	**Performance Level**
Story 8	453305	**1.15**	Position Retention
Story 7	452859	**1.33**	Position Retention
Story 6	452327	**1.52**	Position Retention
Story 5	452214	**1.65**	Position Retention
Story 4	451224	**1.68**	Position Retention
Story 3	450981	**1.59**	Position Retention
Story 2	450394	**1.27**	Position Retention
Story 1	449797	**0.60**	Operational

CASE I WALL Y1	**Element ID Number**	**Drift Ratio (%)**	**Performance Level**
Story 8	453667	**1.14**	Position Retention
Story 7	453212	**1.32**	Position Retention
Story 6	452769	**1.50**	Position Retention
Story 5	451878	**1.64**	Position Retention
Story 4	451714	**1.70**	Position Retention
Story 3	450841	**1.60**	Position Retention
Story 2	450505	**1.28**	Position Retention
Story 1	450011	**0.60**	Operational

Table 4.13. *The performance levels of Wall X1 (above) and Wall Y1(below) according to the average of maximum drift ratio values from seven ground motion records for Case II*

CASE II WALL X1	**Element ID Number**	**Drift Ratio (%)**	**Performance Level**
Story 8	453305	**1.72**	Position Retention
Story 7	452859	**1.99**	Position Retention
Story 6	452327	**2.27**	Life Safety
Story 5	452214	**2.47**	Life Safety
Story 4	451224	**2.52**	Life Safety
Story 3	450981	**2.37**	Life Safety
Story 2	450394	**1.90**	Position Retention
Story 1	449797	**0.90**	Operational

CASE II WALL Y1	**Element ID Number**	**Drift Ratio (%)**	**Performance Level**
Story 8	453667	**1.71**	Position Retention
Story 7	453212	**1.98**	Position Retention
Story 6	452769	**2.25**	Life Safety
Story 5	451878	**2.45**	Life Safety
Story 4	451714	**2.54**	Life Safety
Story 3	450841	**2.40**	Life Safety
Story 2	450505	**1.91**	Position Retention
Story 1	450011	**0.90**	Operational

Table 4.14. *The performance levels of Wall X1 (above) and Wall Y1(below) according to the average of maximum drift ratio values from seven ground motion records for Case III*

CASE III WALL X1	Element ID Number	Drift Ratio (%)	Performance Level
Story 8	451965	**1.09**	Position Retention
Story 7	451464	**1.29**	Position Retention
Story 6	451360	**1.50**	Position Retention
Story 5	450493	**1.66**	Position Retention
Story 4	449956	**1.73**	Position Retention
Story 3	449691	**1.64**	Position Retention
Story 2	449541	**1.31**	Position Retention
Story 1	448963	**0.61**	Operational

CASE III WALL Y1	Element ID Number	Drift Ratio (%)	Performance Level
Story 8	452324	**1.12**	Position Retention
Story 7	451837	**1.32**	Position Retention
Story 6	451021	**1.52**	Position Retention
Story 5	450931	**1.68**	Position Retention
Story 4	450304	**1.76**	Position Retention
Story 3	449694	**1.68**	Position Retention
Story 2	449544	**1.35**	Position Retention
Story 1	449401	**0.63**	Operational

Peak acceleration demands and maximum drifts of focused walls in case models are evaluated in accordance with limit values from literature and codes (ASCE/SEI 41-13 (2013), TEC (2007), FEMA 356 (2010) & Henkel *et al*. (2008). For the application of walls, the requirements and estimated building performances are specified. The next step is sharing the results with all project stakeholders such as architects, engineers, project manager, contractor, sub-contractor, site manager, client, *etc*.

4.3. Evaluation and Sharing of the Outputs within BIM Environment

BIM concept in the AEC/O industry creates an information-sharing platform for all project team members. Thus, the process, findings and change requests of each team member from various disciplines are sent to a shared common model so this model is always up-to-date and accessible. To demonstrate this framework, seismic design outputs from the previous section are sent to the Revit building model which will serve as a guide for the seismic design of elements in the design process. In Excel, the needed data for seismic design of drywalls are specified and produced information regarding requirements is shared for the construction process in the Revit building model. For the data exchange between Excel and Revit, an add-in, IMAGINiT Utilities for Revit is used. With the IMAGINiT tool, according to the element category, data of each parameter can be imported and exported smoothly. A number of usual parameters about each category are existing. For drywall elements, wall category is used and in this category, many exchange parameters can be chosen like category, cost, comments, description, design options, keynote, manufacturer, model, image, type, type name and comments, type id, course scale fill pattern and color, *etc*. In this study, the data about seismic parameters are shared between different software thus, new shared parameters are created in the Revit model. The exchanged seismic data such as acceleration values, profile types, anchoring distances, drift ratios, are constituted as shared parameters under the seismic group instead of project parameters since shared parameters appear in schedules and tags. After the creation of the parameters, they are assigned to the walls category. Then, an import-export template between Revit and Excel is organized including seismic data parameters (Figure 4.13).

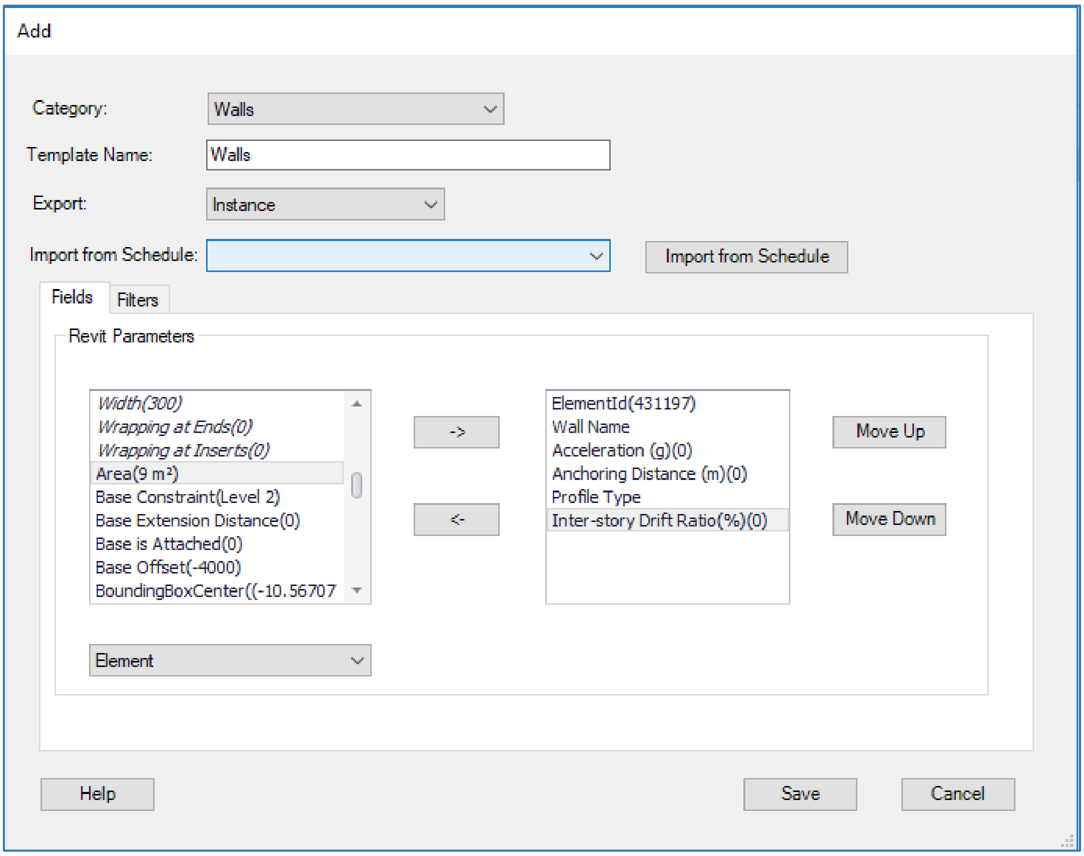


Figure 4.13. Creating an import-export template for Revit - Excel link

For drywall elements, the walls category is generated by using created seismic parameters. In the import-export template of the Revit-Excel link, the element id number parameter must be chosen as an identifier column since, in the data exchange process, the information is coded with element id numbers. For this study, the import template includes following seismic shared parameters for three case models; Element Id, Wall Name, Acceleration (g), Profile Type, Anchoring Distance (m), Drift Ratio (%) and Warnings. The output data in Excel (given in Appendix section) is imported to Autodesk Revit by making use of the Revit-Excel link provided by IMAGINiT. In the Revit interface, the imported data can be visible in element properties. Additionally, in Revit, the wall tag category is created to illustrate the imported seismic data in the plan view. The demands obtained by linear dynamic analysis and their comparison with the estimated capacity of the walls revealed the fact that the demands of each partition wall in the same project are different and their installation should not be stereotype. The name, peak acceleration value, used profile type, anchoring distance of walls as well as drift ratio value on walls are labeled in the wall tag category. According to drift demand on each wall, building performance levels are specified and wall tag colors are varied; operational (green), position retention (blue) and life safety (red).

In order to lay bare differences of the seismic demands for partitions located in different stories in the same project, the results of walls located at the first, fourth and eighth floor levels are illustrated separately for three cases in the following figures. With the help of the representation techniques, the results can be observed by all relevant team members.

Case I - Representation of Analysis Results in Revit Plan View

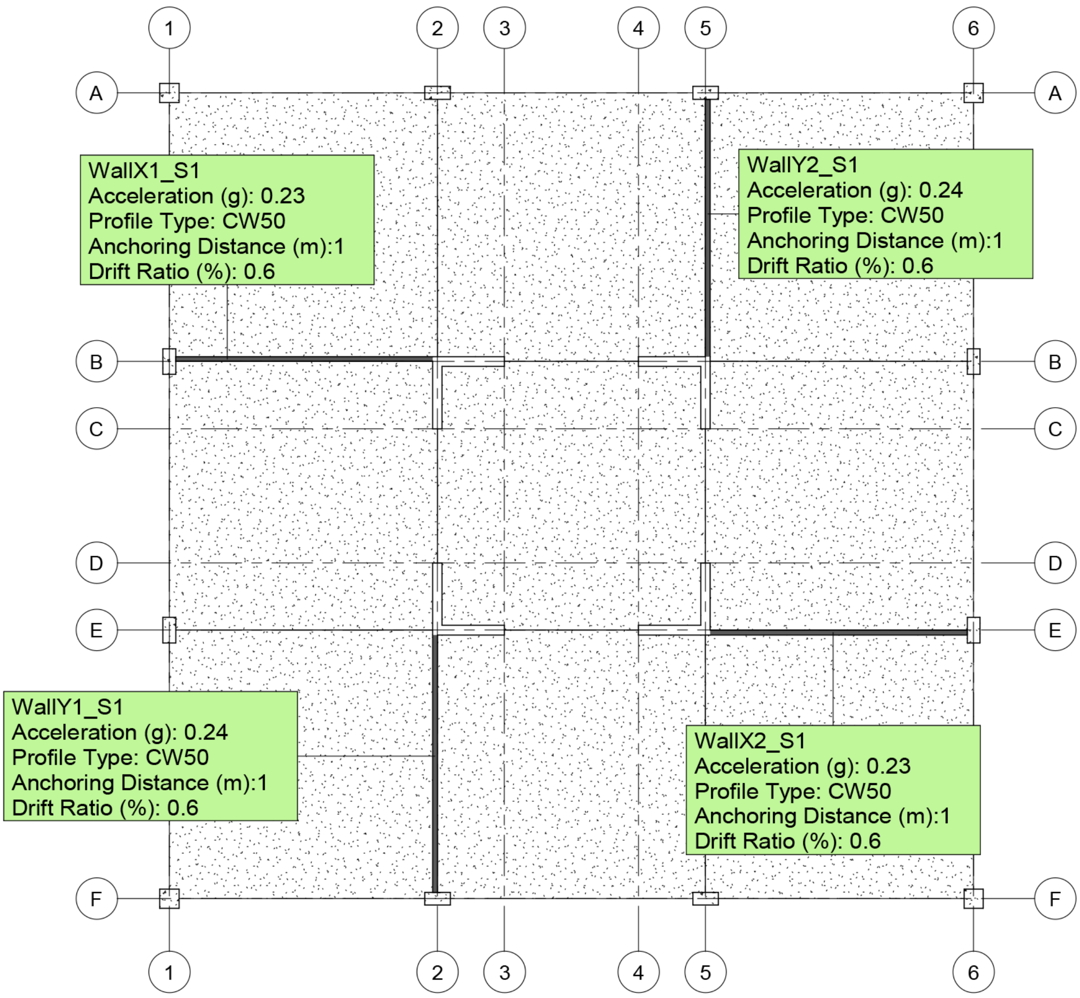


Figure 4.14. Seismic design requirements for drywalls located at the first floor level of Case I imported to Revit (green color refers to 'Operational Nonstructural Performance Level' designated by drift ratio)

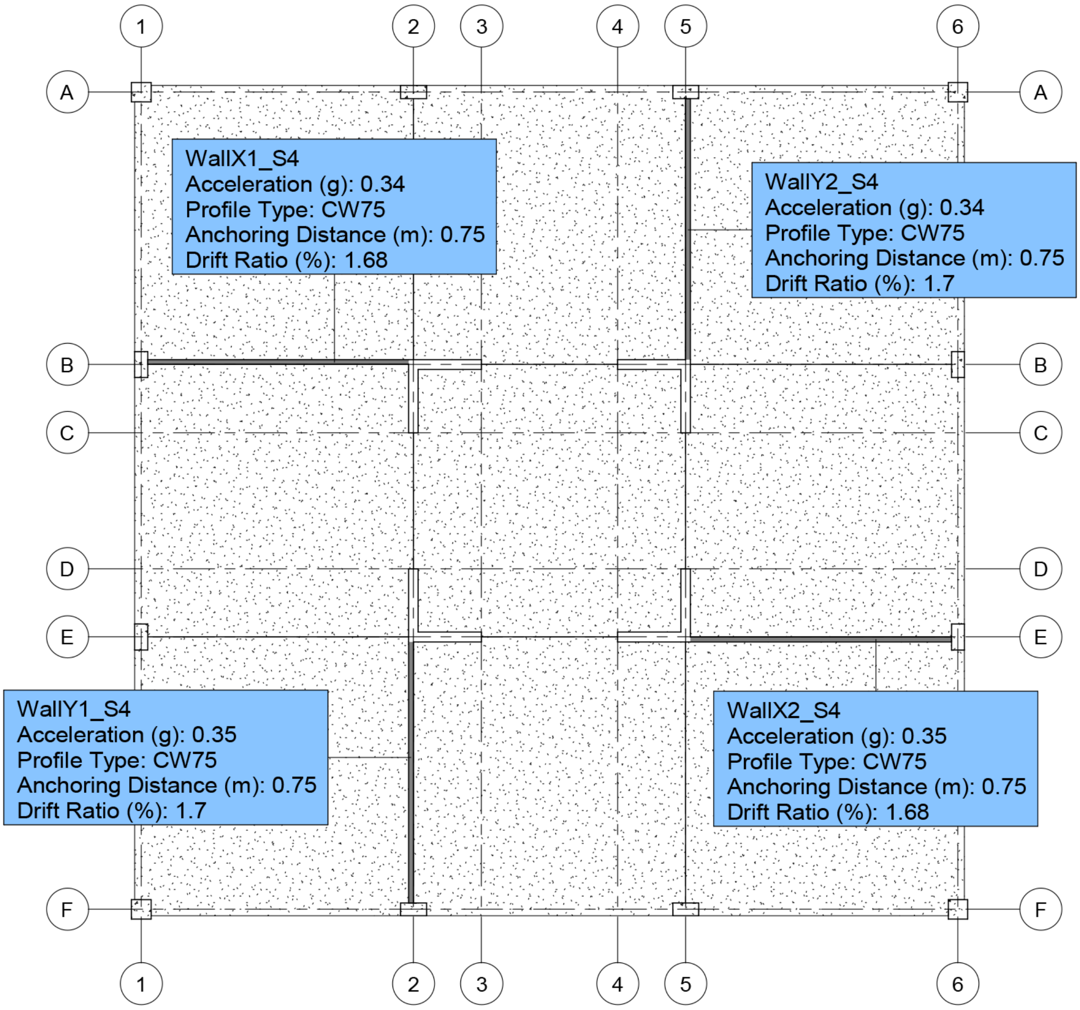


Figure 4.15. Seismic design requirements for drywalls located at the fourth floor level of Case I imported to Revit (blue color refers to 'Position Retention Nonstructural Performance Level' designated by drift ratio)

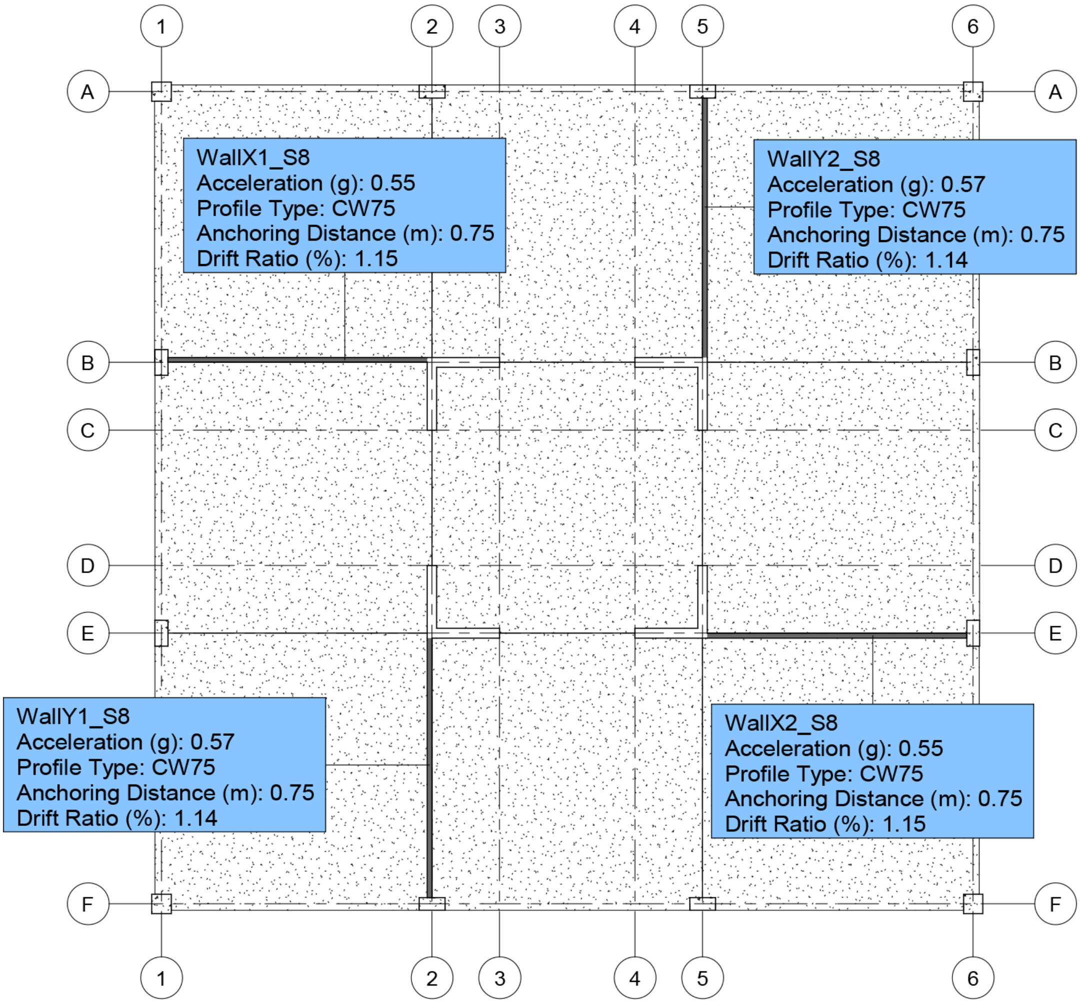


Figure 4.16. Seismic design requirements for drywalls located at the eighth floor level of Case I imported to Revit (blue color refers to 'Position Retention Nonstructural Performance Level' designated by drift ratio)

Case II - Representation of Analysis Results in Revit Plan View

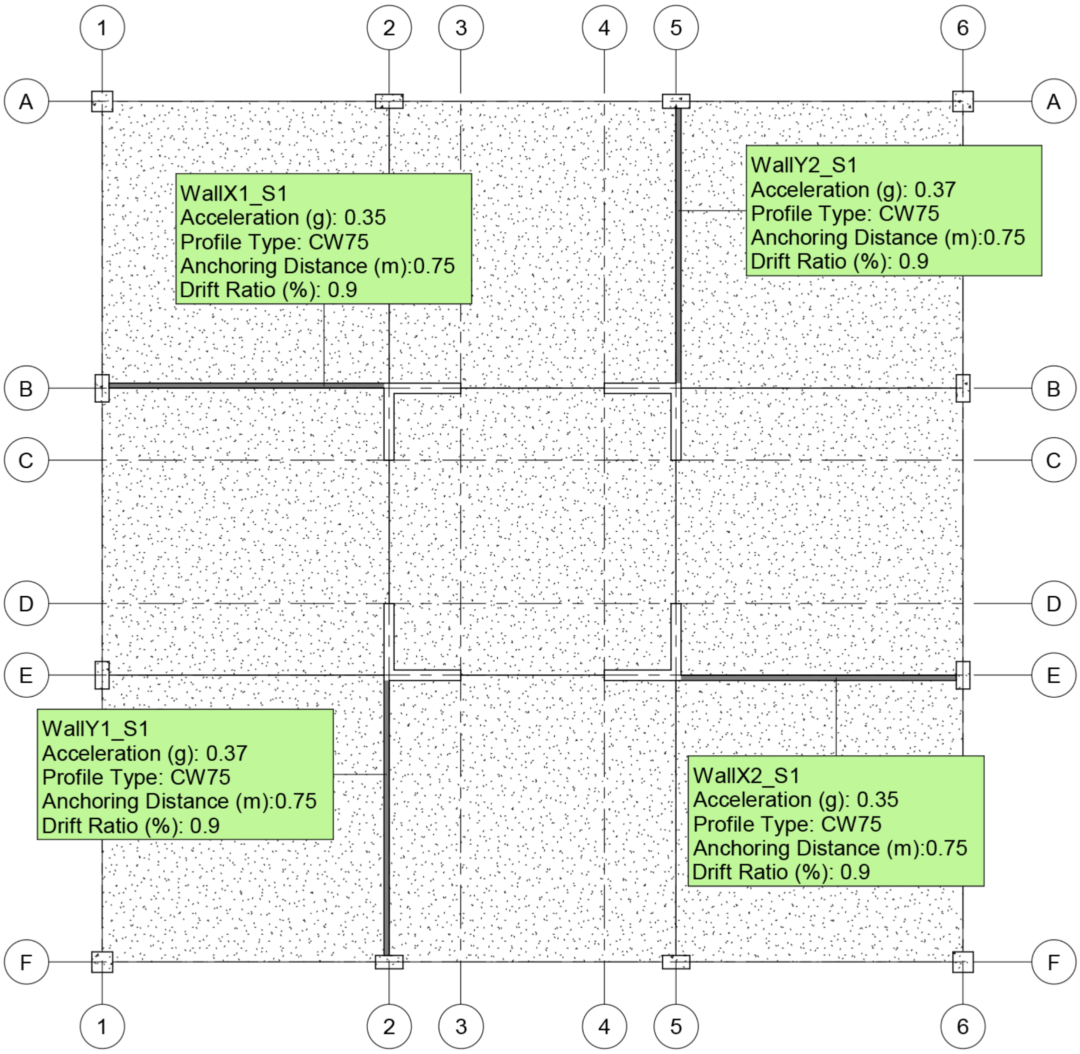


Figure 4.17. Seismic design requirements for drywalls located at the first floor level of Case II imported to Revit (green color refers to ‘Operational Nonstructural Performance Level’ designated by drift ratio)

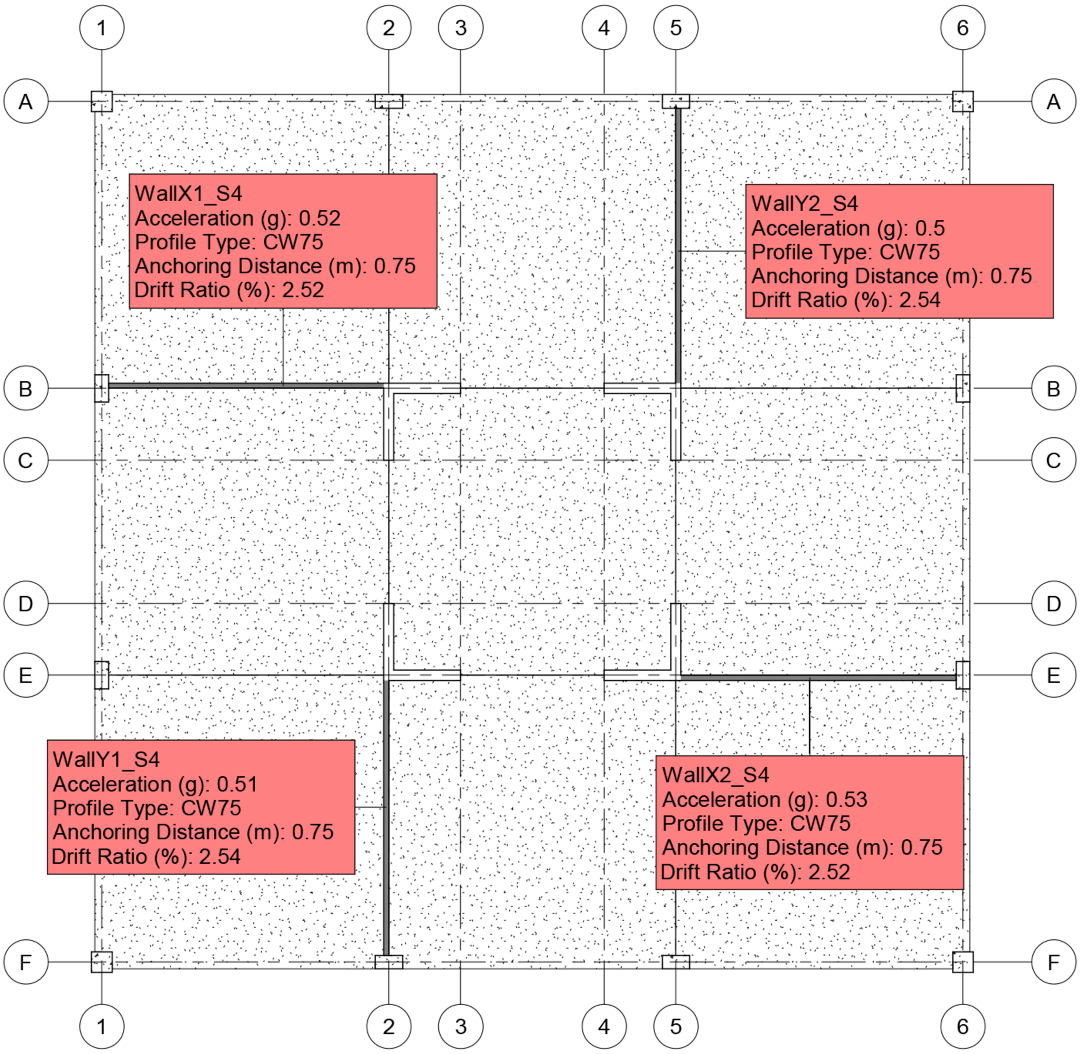


Figure 4.18. Seismic design requirements for drywalls located at the fourth floor level of Case II imported to Revit (red color refers to 'Life Safety Nonstructural Performance Level' designated by drift ratio)

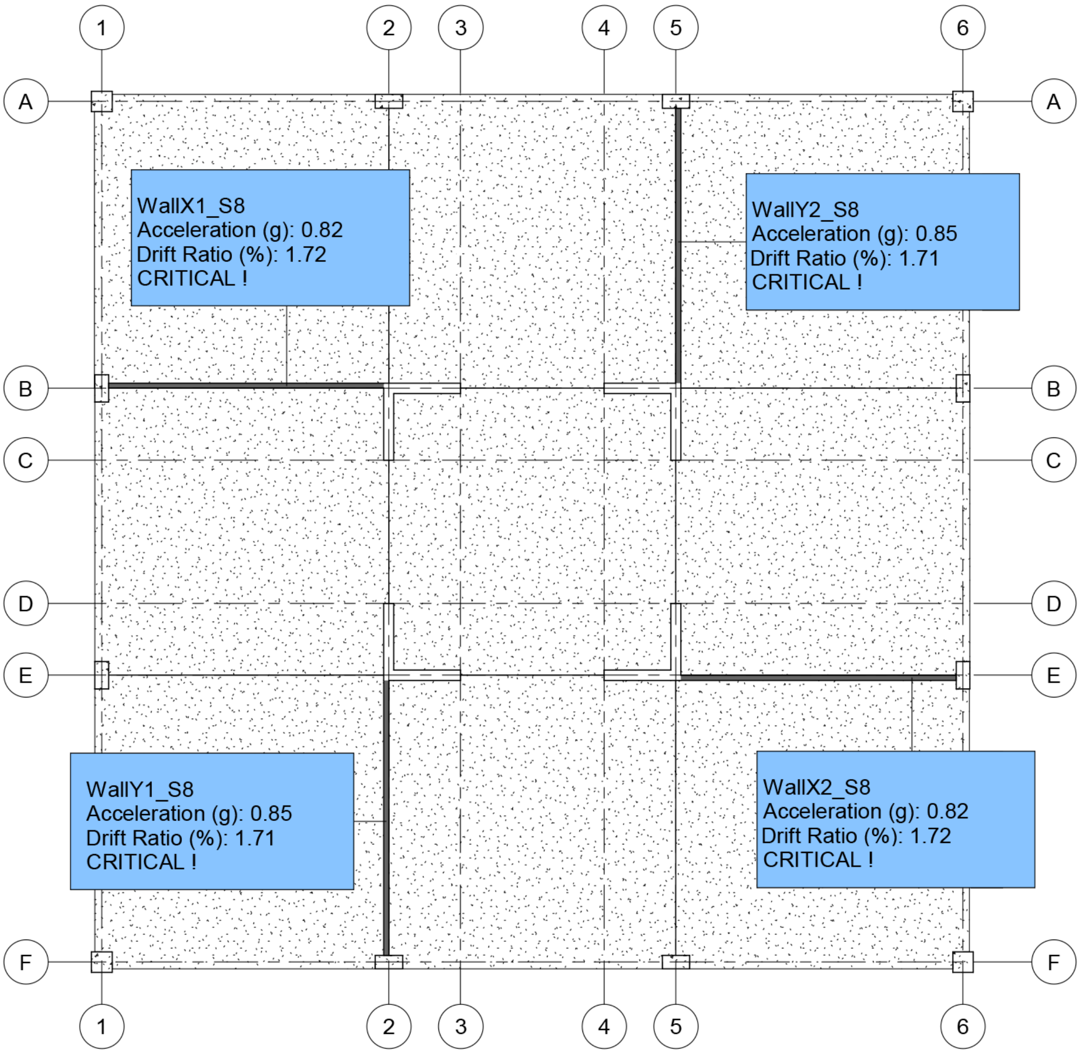


Figure 4.19. Seismic design requirements for drywalls located at the eighth floor level of Case II imported to Revit (blue color refers to 'Position Retention Nonstructural Performance Level' designated by drift ratio)

Case III - Representation of Analysis Results in Revit Plan View

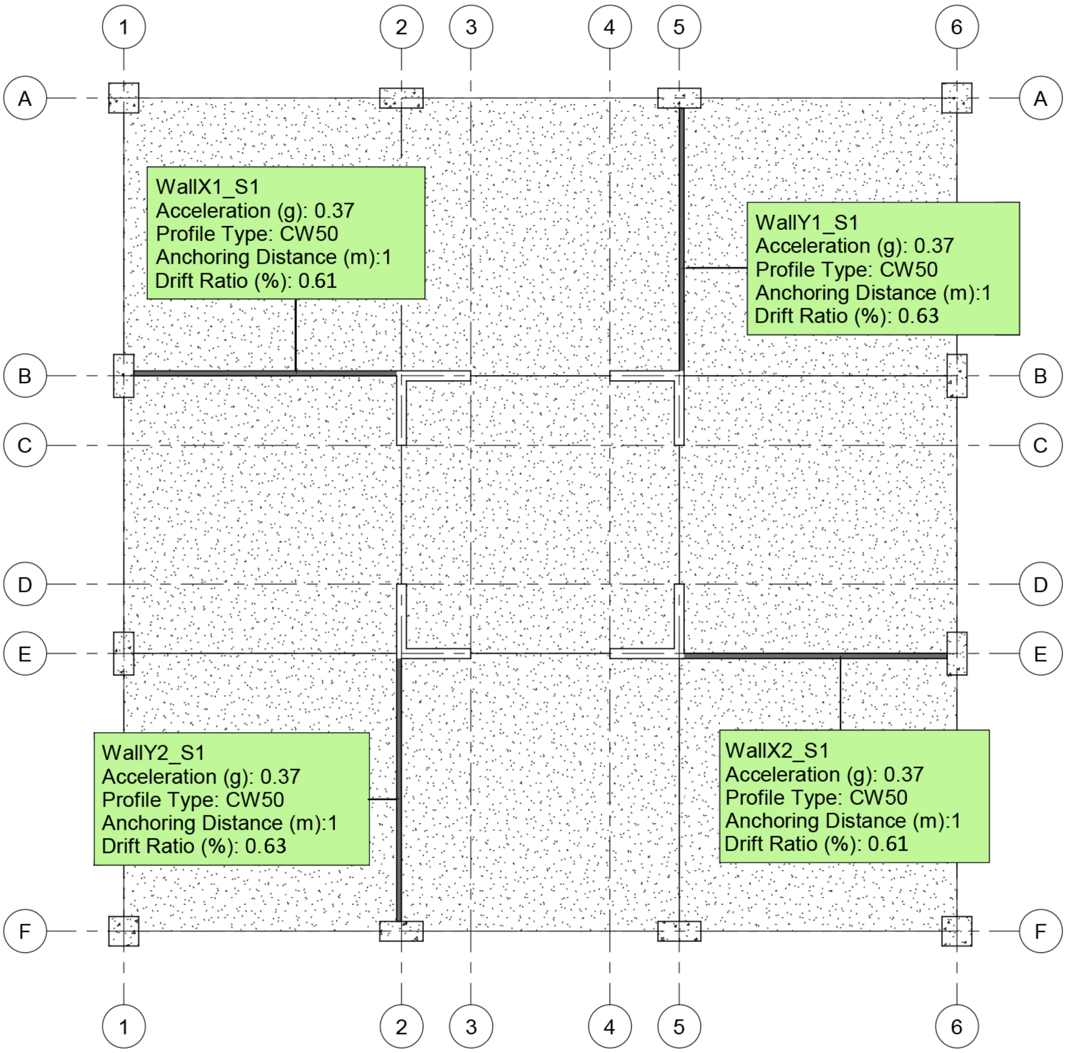


Figure 4.20. Seismic design requirements for drywalls located at the first floor level of Case III imported to Revit (green color refers to 'Operational Nonstructural Performance Level' designated by drift ratio)

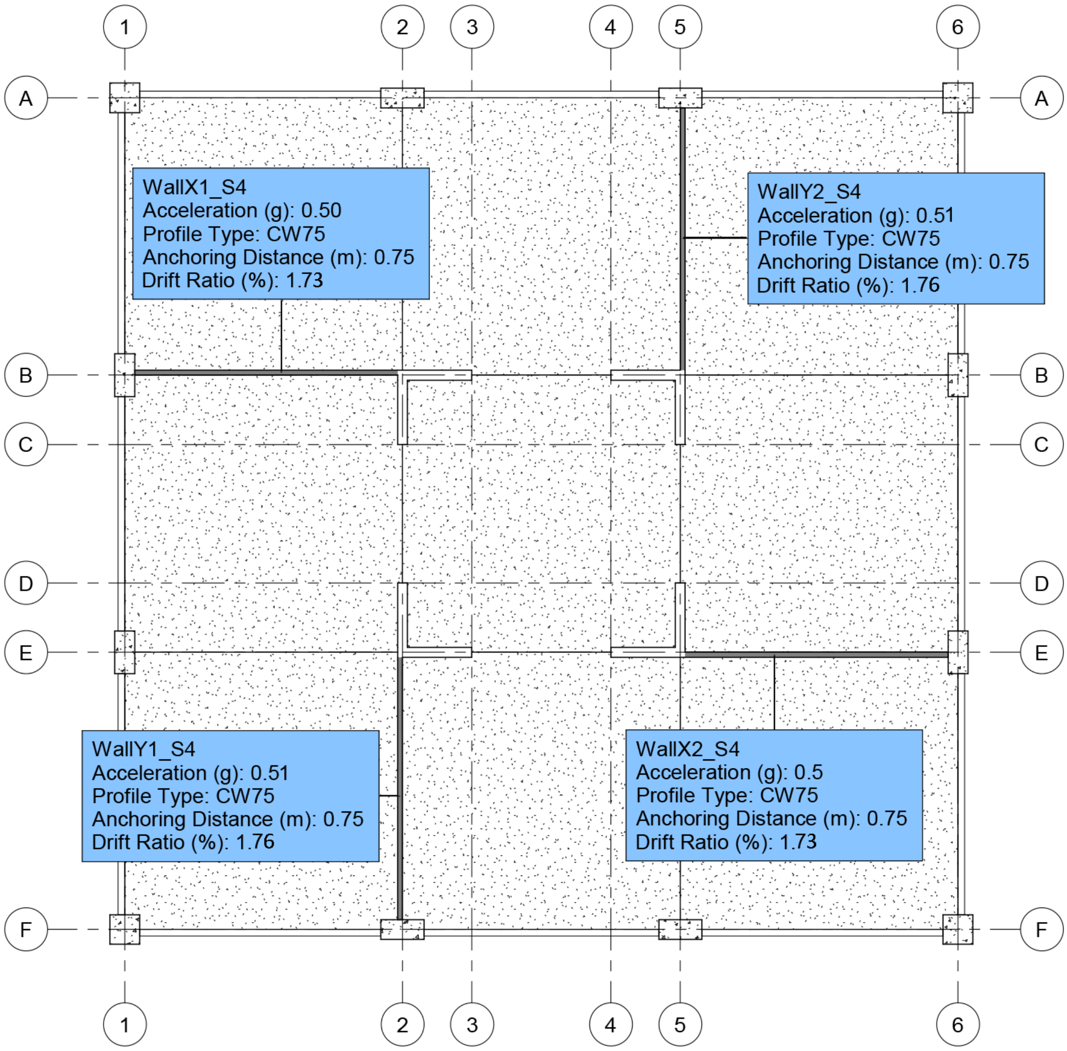


Figure 4.21. Seismic design requirements for drywalls located at the fourth floor level of Case III imported to Revit (blue color refers to 'Position Retention Nonstructural Performance Level' designated by drift ratio)

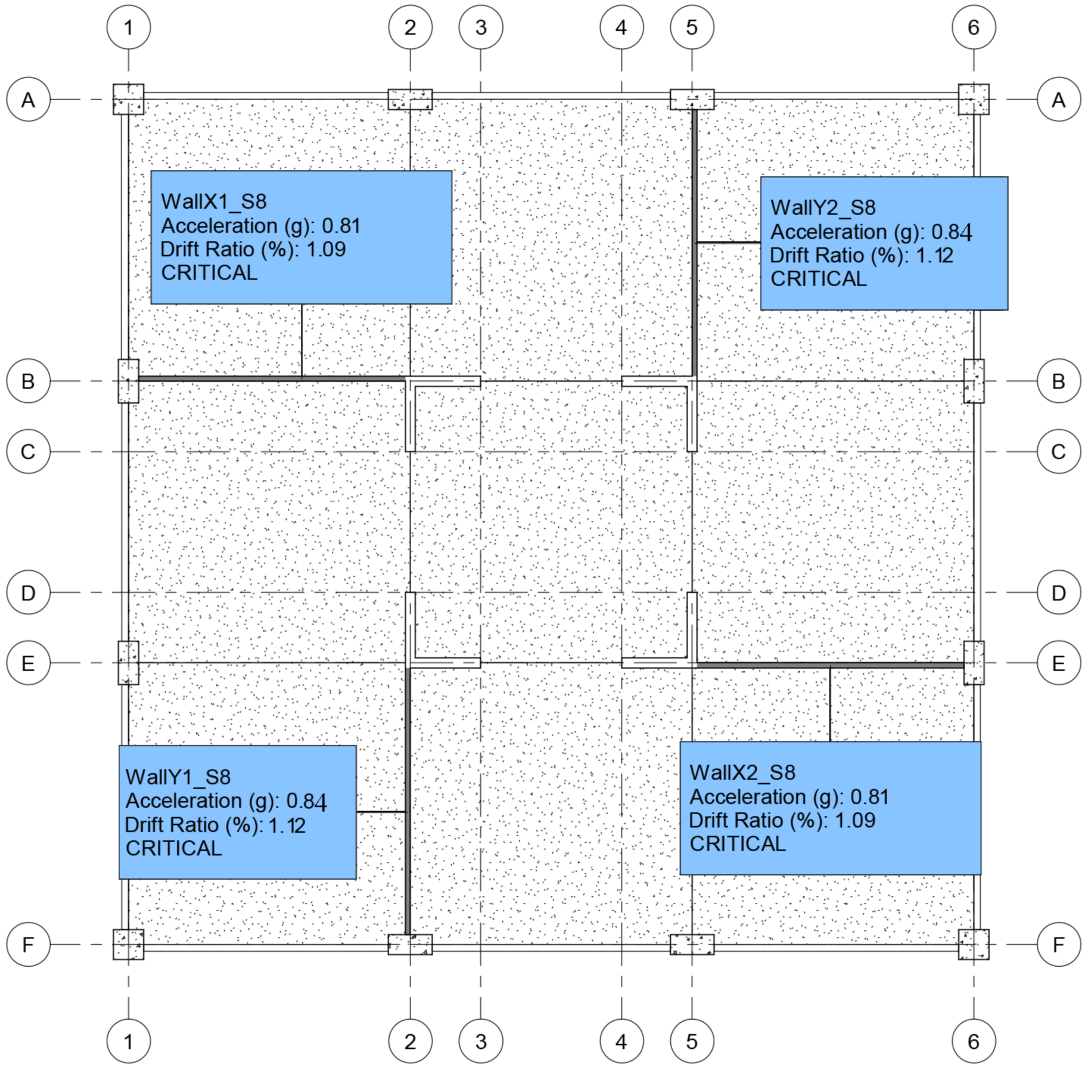


Figure 4.22. Seismic design requirements for drywalls located at the eighth floor level of Case III imported to Revit (blue color refers to 'Position Retention Nonstructural Performance Level' designated by drift ratio)

Analysis results are systematically and effectively returned to the main Revit building model as given in the explanations and figures. Moreover, the integrated project realization process continues in an intelligent building model. In Revit software, by making use of the imported analysis results, seismic design force can be calculated inside the BIM flowchart.

4.3.1. Calculation of Seismic Design Force in Revit Interface

In this section, out-of-plane seismic design forces at the center of partition walls are obtained in addition to the mentioned seismic demands above. The determination of seismic force demands in the design process enables the seismic design process. The horizontal earthquake force equation based on ASCE/SEI 7-10 is indicated in the previous chapter. In this equation, maximum acceleration (a_i) taken from structural analysis and component operating weight (W_p) are variables while the remaining inputs are constant values taken from reference tables in ASCE/SEI 7-10. In this study, component amplification factor (a_p), the torsional amplification factor (A_x), component Importance Factor (I_p) are taken 1.0 whereas component response modification factor (R_p) is taken 2.5 (Figure 4.23).

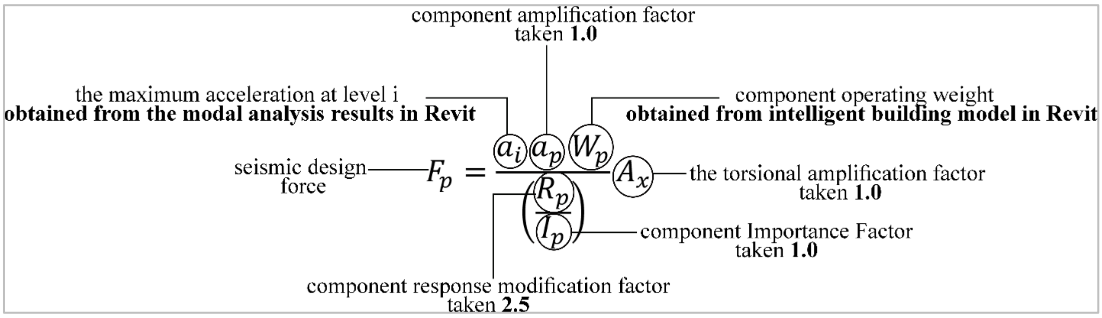


Figure 4.23. Seismic force equation given in ASCE-SEI 7-10 and corresponding values

The variable inputs (a_i and W_p) in the equation are supplied by the Revit building model. The maximum drywall acceleration values received from dynamic analyses are imported successfully to Revit and assigned to each wall element properties. Another variable input, component operating weight is also available in the Revit model trustworthily because the data about wall type and equipment on walls are existing obviously from the beginning of the project and so the weight of each wall is provided clearly. If any changes occur during the process, the updated building model will be available for all stakeholders. In the Revit model, all equipment are real objects in the logic of BIM technology thus each partition can be evaluated on its own merits instead of generalized or stereotyped acceptance criteria. Before starting the calculation process, shared force parameter is created. For the seismic force calculation in Revit interface, schedule/quantities are created for the wall category and required parameters are chosen for the scheduled field. Wall name, comments, wall area, wall weight, acceleration, equivalent constants, and seismic force columns are generated in the schedule. In the comments column, the hanging equipment on the walls and their total weights are listed. Weight per unit area of equipment is calculated and added to wall unit weight and so operating unit weight is obtained. The unit weight of the double layer cladding metal stud gypsum board wall is taken as 50 kg/m2 as given by Henkel, Holl & Schalk (2008). Acceleration values are tabularized automatically and constants are added to the table. Finally, uniformly distributed seismic design force for each drywall is calculated. The seismic force calculation schedule of drywalls can be seen in the Revit interface in detail as shown in Appendix B. For all three cases, seismic design force values obtained for drywalls located at first, fourth and eighth floor levels are listed in Table 4.15 to show differences in the requirements.

Table 4.15. *Uniformly Distributed Seismic Design Force on Drywalls located at first, fourth and eighth floor levels for Case I, Case II &Case III (units in kgf/m^2)*

Case I	Wall X1	Wall X2	Wall Y1	Wall Y2
Story 8	12.21	12.1	11.4	11.4
Story 4	6.8	7	7.7	7.2
Story 1	4.8	4.6	5.3	5.28

Case II	Wall X1	Wall X2	Wall Y1	Wall Y2
Story 8	16.7	18.04	17	19.04
Story 4	10.78	11.79	10.38	10.0
Story 1	7.0	7.38	8.22	7.5

Case III	Wall X1	Wall X2	Wall Y1	Wall Y2
Story 8	17.2	17.9	17.1	16.8
Story 4	10.0	11.3	10.2	10.0
Story 1	7.4	7.8	7.4	7.5

It is obviously seen from the tables that the seismic force demands of each wall in a project are not the same. In a similar manner, the design and installation of the drywalls do not have to be standard. Due to different acceleration values on different floors, various seismic force values act on walls. In addition to acceleration value, the wall operating weight is differential owing to hanging equipment on the walls. The function of case models is office buildings, therefore, the hanging equipment on drywalls could be huge screens, signboards, embedded bookshelves, air handling units, sanitaryware type materials and thus their weight should be added to the own weights of walls when calculating the horizontal force on members. For the case models, some of the partitions have mentioned equipment on them and so the seismic design force (uniformly distributed seismic design force multiplied with the wall area) of symmetrical walls located at the same level differs from each other. Besides these difference, seismic design force acting on the bare drywalls (without any equipment on it) located at the eighth floor is approximately 2.4 times more than seismic design force for bare drywalls located at first floor. Therefore, in the design and construction process, seismic parameters should be taken into consideration in accordance with uploaded seismic data to the shared building model.

CHAPTER 5

CONCLUSION

5.1. Summary of Research

The growing trend in the AEC/O industry, Building Information Modelling (BIM) technology and it's potentials triggers this study. BIM technology is promising for critical industry problems so one of the problematic and serious issues of the AEC/O industry is seismic damage to non-structural elements. The performance objectives of a building are not only related to the structural components but also related to non-structural elements. Therefore this research investigates the efficacy of using BIM technology in the seismic design and installation of non-structural components. This study demonstrates that by utilizing BIM, it is possible to store, manage and disseminate the information about the seismic performance parameters of lightweight partitions.

This study is operated into two branches; BIM and seismic demands of drywalls. In the examination of the seismic demands of drywalls, input and output data are exchanged by the help of Application Programming Interface (API) method within BIM workflow. In order to observe the seismic demands on drywalls, three case models are created in Revit. The required elements are dispatched from Revit building model to ETABS with the aid of CSIXRevit plug-in. Assuming that the sample case study buildings are located in Kadıköy-Istanbul, one of the zones with the highest seismicity in Istanbul, code-compliant structural design has been achieved. Then, linear dynamic analyses are carried on for three case models in ETABS in accordance with chosen ground motion records; compatible with 10% in 50-year and 2% in 50-year ground motion spectrum. The results obtained from ETABS are exported to MS Excel. Peak accelerations and maximum drift ratios of focused drywalls are used for performance assessment because partitions are both acceleration and displacement of sensitive elements. The results showed that, for a given performance level, the seismic capacity requirements of each wall are different so the design and installation of drywalls should be specific to demands. The limiting acceleration values of drywalls, is taken from reference documents of a production company. Under the guidance of this information, wall type, used profile type, anchoring distances are specified. Similarly, drift ratios of drywalls and performance levels of components are determined. The evaluated data in Excel has been sent to Revit via using the link provided by IMAGINiT add-ins. In Revit, an updated building information model includes seismic demands data and outputs inferred by comparing the demands and capacity of walls. Additionally, the seismic design force of drywalls is calculated in Revit interface thanks to the information in the integrated building model. Thus, the presented workflow reveals the fact that it is possible for all team members to access the updated required data during the project realization process.

This study showed that seismic demand on each drywall is different and drywalls can be designed and installed conveniently in accordance with their own conditions by making use of BIM. Above all, BIM technology makes it possible for the systematized and automated seismic studies of these elements by accelerating and integrating the process. Adopting BIM technology eases the whole processes of the project such as design, construction, operation, and demolition. It is the same for the construction process. The site managers can actively follow their daily tasks by using BIM compatible tools. Ordering of materials, their transportation and storage, application, briefing, and work planning can be organized over the BIM technology. The details of orders, transportation time and storage place of materials are specified by using building information model and compatible tools. Then, application type of elements, which has been already marked on the digital model in the design stage, are shared with workers on the site. Moreover, organizing the site conditions with BIM working principles can settle the conflict and develop construction of the industry.

5.2. Main Results and Assessments

The main aim of this research is to investigate the potentials of Building Information Modelling (BIM) technology on the subject of seismic design and the installation of non-structural building elements. In line with this objective, it is focused on the seismic performance of metal stud lightweight partitions by using BIM technology, which is the main enabler for this research. The first and key branch of this study is maintaining the integrated and coordinated project realization process within BIM loop in the area of seismic design whereas the second is the determination of seismic demands for drywalls and evaluation of the results for design and installation. The results can be listed as:

- Application Programming Interface (API) data exchange method provides data flow smoothly with the help of plug-ins and add-ins between different software applications. In the transition process of data from modeling software, Revit, to the structural analysis tool, ETABS (ver. 16), CSIXRevit plug-in works swimmingly. Analysis results in ETABS are exported to Excel at short notice, which is directly related to ETABS. Evaluated outputs in Excel are sent to Revit successfully by using an add-in called 'IMAGINiT utilities for Revit'. In Revit interface, by using the imported data, operations can continue. Consequently, all founded data operated by various software applications can be easily implemented to Building Information Model in order to update and share information with all stakeholders.

- The seismic demands on drywalls depend on location in the building. According to obtained data from linear time history analysis results, the peak acceleration value of drywalls located at the eighth floor is 2.40 times for Case I; 2.34 times for Case II; 2.49 times for Case III more than peak acceleration value of drywalls located at first floor. Additionally, by using peak acceleration values and wall height data, used profile types and anchoring distances can be specified for the installation of each drywall. For some partitions having higher acceleration on top floors, proper profile type and anchoring distance do not exist for the selected type of drywall, so these walls are noted as ‘Critical’ and informed responsible disciplines in Revit interface.

- The seismic design force values on drywalls based on Eq-1 taken from ASCE/SEI 7-10. According to the Eq-1, maximum accelerations and component operating weight, which are changing values depending on each drywall, are used to determine seismic design forces for drywalls. The maximum acceleration values are obtained from modal analysis results and sent to Revit building model for each drywall element. The operating weight of the walls is obtained by adding the own weight of walls and weight of the hanging equipment on walls. In Revit interface, maximum accelerations and operating unit weights of each drywall can be existing so the seismic force demands for each drywall can be calculated in the building model interface. For three case models, seismic design forces are calculated in Revit interface (shown in Appendix B). The computed seismic force values for drywalls on the eighth floor are 2.72 times more than the seismic force of drywalls located on the first floors. As a result, the seismic force demands of each drywall are various and so, the seismic design and installation of each drywall should be special instead of the stereotyped application.

- The maximum drift ratio demands on drywalls for three case models are obtained from linear dynamic analyses. The target building performance levels for drywalls during the earthquake are determined in accordance with drift ratio limits. Corresponding to the limitations, performance levels of drywalls in the case models are obtained. Outcomes show that different drift ratio of drywalls in different stories reveal various performance levels in a building so these elements should be redesigned according to the main target performance level of the building.

- Three different case results justify that the stereotyped and standardized production of drywalls for all projects, what is applied in the AEC/O industry currently, are not proper to performance-based seismic design principles. According to the design of structural elements and levels of seismicity, the responses and requirements of drywalls are different. Hence, special seismic design and installation for each drywall are required. With the help of the developments in BIM maturity level, during the construction and operational process of the buildings, site control, installment check, ordering and maintenance of drywalls can be possible.

- All analysis results, outputs, and assessments for each wall element return to the main building model without data and time loss. The imported data can be exhibited in the plan view by arranging the tag category. The proposed methodology enables seismic inputs to be available in a compact model for the seismic design of drywalls in a more realistic way. Thereby, the benefits of BIM technology in the seismic design of metal stud drywalls are indisputable.

5.3. Limitations of the Study

The study has some limitations in the area of both seismic studies and BIM process as explained below:

In the current BIM maturity level (Level 2), full collaboration and sharing information among different team members are the main focus of interest. For the full integration and optimization during the life-cycle of the buildings, the industry should shift the BIM level to Level 3 (iBIM) but Level 3 has not yet been fully defined. Therefore, the limitations in BIM technology can make difficult special seismic design for each element in terms of site control, installment check and ordering of materials.

In the data exchange process, in order to achieve a reliable data transition between different applications, additional plug-ins are used. By making use of plug-ins in the flowchart of the study, the proposed path is completed without warning and error. However, the use of some additional tools in the process can effect negatively the efficiency of the time and cost management during the project. Therefore, BIM compatible tools still need to develop to work perfectly in harmony.

In the scope of this thesis, with the help of the BIM technology, the seismic demands and capacity of the drywall systems are investigated by using three case studies, yet in the Case II and Case III, according to a few of analysis results under the chosen seven ground motion records, the drift ratio of the structure can exceed the limiting ratio (2%). However, the determination of the performance levels of the buildings is developed by the average values of the results from the seven ground motion records. Although there is a possibility to collapse of the structure of the buildings for the high drift ratio (higher than 2%), it is assumed the structure survives with the heavy damages. Thus, the seismic behavior of non-structural elements becomes a critical subject for the life-safety in a heavy damaged building and so the performance level of drywalls are evaluated in Case II and III.

The version of ProtaStructure 2018 used in the first stage of this study, doesn't allow to consider TEC2019. Therefore, the building models were seismically designed according to TEC2007.

In order to obtain the seismic demand values on drywalls, linear time history analysis was carried out. Non-linear time history analysis could be considered for the evaluation of the seismic demands on drywalls. Instead of code-based 475-year and 2475-year return period spectra, site-specific hazard information can be used both for design and record selection.

The building models, used in the case studies, have a regular structural system. The methodology of this study was not performed for an irregular structure. Additionally, all case models had eight-story levels. The effect of differentiation in the number of floors in seismic demands on drywalls was ignored for this study.

Some of the BIM compatible application tools mentioned in the third chapter, SOFISTiK and Robot Structural Analysis, are promising tools in terms of interoperability with Revit. Yet, the capacity of these tools in the area of seismic analysis was not explored. Moreover, the data exchange by using IFC model between Revit and SOFISTiK could not be checked.

5.4. Recommendations for Future Research

Major output of this study is that state of art BIM technology can accelerate and automate the seismic design and installation of metal stud drywalls by presenting seismic demands on elements as an input data in building information model during design and construction process. The proposed method for this research can be extendable to develop seismic design and installation of other types of non-structural building elements. In this manner, required seismic demand data about all non-structural elements can exist in the main coordinated building model before the construction starts. Responsible disciplines take relevant data and so seismically designed non-structural elements are ready for the implementation phase. This advance can improve the seismic behavior of non-structural elements and reduce earthquake losses arising from non-structural damage.

In the current application in the industry, almost all drywalls in the building are installed identically. However, analysis results illustrated that the seismic demands of each drywall are different. Moreover, three different cases are examined and the seismic requirements of drywalls are different so the current application standards are either insufficient for top floor partitions or overdesigned for bottom floor drywalls. Therefore, the total cost of the standard production of drywalls can be compared to the total cost of the seismically designed case. Standard application method may not satisfy the demands then seismic damage to drywalls is inevitable For the overdesigned case, loss of money can be estimated as the next step of this study by making some comparisons. For this process, BIM provides great potential because it simplifies and catalyzes cost estimation process as quantity take-off of drywalls is taken from an intelligent building model easily. Therefore, the profit-loss account comes to light fast and is shared with team members.

In the AEC/O industry, likewise the seismic damage to building elements, there are critical issues such as fire, wind, *etc*. These issues also threaten life and property safety like seismicity so BIM potentials should be investigated for other problematic areas in the industry.

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APPENDICES

A. EVALUATION OF THE ANALYSIS RESULTS IN EXCEL

Table A.1. *Outputs of Case I for all drywalls in the Excel, Ready for importing to Revit*

Element Id	Wall Name	Acceleration (g)	Anchoring Distance (m)	Drift Ratio(%)	Profile Type
449797	WallX1_S1	0.23	1	0.60	CW50
449893	WallX2_S1	0.23	1	0.60	CW50
450011	WallY1_S1	0.24	1	0.60	CW50
450115	WallY2_S1	0.24	1	0.60	CW50
450271	WallY2_S2	0.25	1	1.28	CW50
450394	WallX1_S2	0.25	1	1.27	CW50
450505	WallY1_S2	0.25	1	1.28	CW50
450631	WallX2_S2	0.25	1	1.27	CW50
450709	WallX2_S3	0.28	1	1.59	CW50
450841	WallY1_S3	0.30	1	1.6	CW50
450981	WallX1_S3	0.28	1	1.59	CW50
451071	WallY2_S3	0.30	1	1.60	CW50
451224	WallX1_S4	0.34	0.75	1.68	CW75
451459	WallY2_S4	0.34	0.75	1.70	CW75
451605	WallX2_S4	0.35	0.75	1.68	CW75
451714	WallY1_S4	0.35	0.75	1.70	CW75
451878	WallY1_S5	0.40	0.75	1.64	CW75
452002	WallX2_S5	0.38	0.75	1.65	CW75
452111	WallY2_S5	0.40	0.75	1.64	CW75
452214	WallX1_S5	0.39	0.75	1.65	CW75
452327	WallX1_S6	0.41	0.75	1.52	CW75
452425	WallY2_S6	0.43	0.75	1.50	CW75
452598	WallX2_S6	0.41	0.75	1.52	CW75
452769	WallY1_S6	0.43	0.75	1.50	CW75
452859	WallX1_S7	0.45	0.75	1.33	CW75
452969	WallY2_S7	0.46	0.75	1.32	CW75
453085	WallX2_S7	0.45	0.75	1.33	CW75
453212	WallY1_S7	0.46	0.75	1.32	CW75
453305	WallX1_S8	0.55	0.75	1.15	CW75
453404	WallY2_S8	0.57	0.75	1.14	CW75
453530	WallX2_S8	0.55	0.75	1.15	CW75
453667	WallY1_S8	0.57	0.75	1.14	CW75

Table A.2. *Outputs of Case II for all drywalls in the Excel, Ready for importing to Revit*

Element Id	Wall Name	Acceleration (g)	Profile Type	Anchoring Distance (m)	Drift Ratio(%)	Warnings
449797	WallX1_S1	0.35	CW75	0.75	0.90	
449893	WallX2_S1	0.35	CW75	0.75	0.90	
450011	WallY1_S1	0.37	CW75	0.75	0.90	
450115	WallY2_S1	0.37	CW75	0.75	0.90	
450271	WallY2_S2	0.38	CW75	0.75	1.91	
450394	WallX1_S2	0.37	CW75	0.75	1.90	
450505	WallY1_S2	0.38	CW75	0.75	1.91	
450631	WallX2_S2	0.37	CW75	0.75	1.90	
450709	WallX2_S3	0.41	CW75	0.75	2.37	
450841	WallY1_S3	0.45	CW75	0.75	2.40	
450981	WallX1_S3	0.41	CW75	0.75	2.37	
451071	WallY2_S3	0.45	CW75	0.75	2.40	
451224	WallX1_S4	0.52	CW75	0.75	2.52	
451459	WallY2_S4	0.50	CW75	0.75	2.54	
451605	WallX2_S4	0.53	CW75	0.75	2.52	
451714	WallY1_S4	0.51	CW75	0.75	2.54	
451878	WallY1_S5	0.59	CW100	0.50	2.45	
452002	WallX2_S5	0.56	CW75	0.75	2.47	
452111	WallY2_S5	0.59	CW100	0.50	2.45	
452214	WallX1_S5	0.57	CW75	0.75	2.47	
452327	WallX1_S6	0.61	CW75	0.75	2.27	
452425	WallY2_S6	0.64	CW100	0.50	2.25	
452598	WallX2_S6	0.61	CW75	0.75	2.27	
452769	WallY1_S6	0.64	CW100	0.50	2.25	
452859	WallX1_S7	0.67	CW100	0.50	1.99	
452969	WallY2_S7	0.69	CW100	0.50	1.98	
453085	WallX2_S7	0.67	CW100	0.50	1.99	
453212	WallY1_S7	0.69	CW100	0.50	1.98	
453305	WallX1_S8	0.82			1.72	CRITICAL
453404	WallY2_S8	0.85			1.71	CRITICAL
453530	WallX2_S8	0.82			1.72	CRITICAL
453667	WallY1_S8	0.85			1.71	CRITICAL

Table A.3. *Outputs of Case III for all drywalls in the Excel, Ready for importing to Revit*

Element Id	Wall Name	Acceleration (g)	Profile Type	Anchoring Distance (m)	Drift Ratio(%)	Warnings
448963	WallX1_S1	0.37	CW50	1	0.61	
449104	WallY1_S1	0.37	CW50	1	0.63	
449233	WallX2_S1	0.37	CW50	1	0.61	
449401	WallY2_S1	0.37	CW50	1	0.63	
449541	WallX1_S2	0.37	CW75	0.75	1.31	
449542	WallY2_S2	0.40	CW75	0.75	1.35	
449543	WallX2_S2	0.37	CW75	0.75	1.31	
449544	WallY1_S2	0.40	CW75	0.75	1.35	
449691	WallX1_S3	0.43	CW75	0.75	1.64	
449692	WallY2_S3	0.45	CW75	0.75	1.68	
449693	WallX2_S3	0.43	CW75	0.75	1.64	
449694	WallY1_S3	0.45	CW75	0.75	1.68	
449956	WallX1_S4	0.50	CW75	0.75	1.73	
450070	WallY2_S4	0.51	CW75	0.75	1.76	
450190	WallX2_S4	0.51	CW75	0.75	1.73	
450304	WallY1_S4	0.50	CW75	0.75	1.76	
450493	WallX1_S5	0.57	CW75	0.75	1.66	
450638	WallY2_S5	0.60	CW75	0.50	1.68	
450747	WallX2_S5	0.56	CW75	0.75	1.66	
450931	WallY1_S5	0.60	CW75	0.50	1.68	
451021	WallY1_S6	0.66	CW75	0.50	1.52	
451115	WallX2_S6	0.62	CW75	0.50	1.50	
451249	WallY2_S6	0.66	CW75	0.50	1.52	
451360	WallX1_S6	0.62	CW75	0.50	1.50	
451464	WallX1_S7	0.71	CW75	0.50	1.29	
451569	WallY2_S7	0.71	CW75	0.50	1.32	
451700	WallX2_S7	0.71	CW75	0.50	1.29	
451837	WallY1_S7	0.71	CW75	0.50	1.32	
451965	WallX1_S8	0.81			1.09	CRITICAL
452121	WallY2_S8	0.84			1.12	CRITICAL
452227	WallX2_S8	0.81			1.09	CRITICAL
452324	WallY1_S8	0.84			1.12	CRITICAL

The output data concerning the seismic demands on drywalls are listed in the specified formats like in the exemplified tables. Thanks to created link between Excel and Revit by IMAGINiT, data exchange process can complete successfully.

B. **CALCULATION OF THE SEISMIC DESIGN FORCE DEMANDS IN REVIT INTERFACE**

In the Revit building model, all required inputs are available to be able to compute seismic force values for each drywall. To realize the calculation in the Revit interface, a key schedule of drywall building components is created. The schedule of seismic force on drywalls includes wall name and area, hanging equipment on walls in the comments, operating unit weight of walls, peak acceleration values, and constants in the formula. In the scope of this study, the function of case models is specified as office buildings so the hanging equipment on walls could be huge screens, signboards, embedded bookshelves, blackboard, sanitaryware type materials. Their unit weight on walls is added to the unit weight of the drywall systems to obtain distributed seismic load on drywalls. The total weight of the used equipment can be accepted approximately in the calculation process as following;

Equipment Type	**Weight**
Screen	25 kg
Signboard	75 kg
Blackboard	50 kg
Embedded Bookshelves	150 kg
Sanitaryware (x5 pieces)	135 kg

The seismic force calculation schedules in Revit for three cases are shown in the following figures as an example of interface.

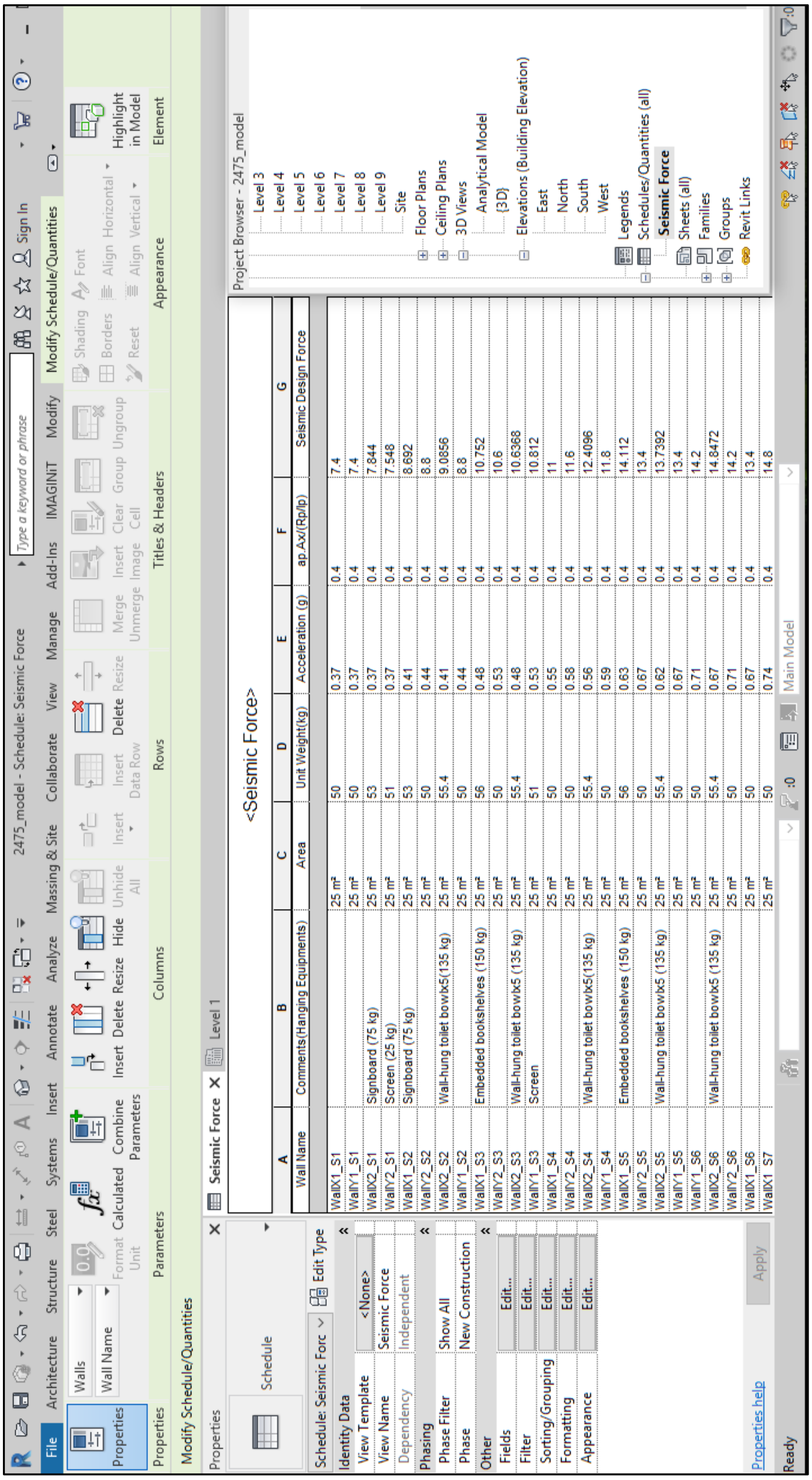

Figure B.1. Calculated seismic design force schedule in Revit interface

Seismic Force

< SEISMIC FORCE FOR CASE I >

A	B	C	D	E	F	G
Wall Name	Comments(Hanging Equipments)	Area	Unit Weight(kg)	Acceleration (g)	ap.Ax/(Rp/Ip)	Seismic Design Force
WallX1_S1	Signboard (75 kg)	27 m²	52.7	0.23	0.4	4.8484
WallX2_S1		27 m²	50	0.23	0.4	4.6
WallY1_S1	Embedded bookshelves (150 kg)	27 m²	55.5	0.24	0.4	5.328
WallY2_S1	Wall-hung toilet bowlx5 (135 kg)	27 m²	55	0.24	0.4	5.28
WallY2_S2		27 m²	50	0.25	0.4	5
WallX1_S2	Signboard (75 kg)	27 m²	52.7	0.25	0.4	5.27
WallY1_S2		27 m²	50	0.25	0.4	5
WallX2_S2		27 m²	50	0.25	0.4	5
WallX2_S3		27 m²	50	0.28	0.4	5.6
WallY1_S3	Blackboard (50 kg)	27 m²	51.85	0.3	0.4	6.222
WallX1_S3		27 m²	50	0.28	0.4	5.6
WallY2_S3	Embedded bookshelves (150 kg)	27 m²	55.5	0.3	0.4	6.66
WallX1_S4		27 m²	50	0.34	0.4	6.8
WallY2_S4	Signboard (75 kg)	27 m²	52.7	0.34	0.4	7.1672
WallX2_S4		27 m²	50	0.35	0.4	7
WallY1_S4	Wall-hung toilet bowlx5 (135 kg)	27 m²	55	0.35	0.4	7.7
WallY1_S5		27 m²	50	0.4	0.4	8
WallX2_S5	Blackboard (50 kg), Screen (25 kg)	27 m²	52.85	0.38	0.4	8.0332
WallY2_S5		27 m²	50	0.4	0.4	8
WallX1_S5		27 m²	50	0.39	0.4	7.8
WallX1_S6		27 m²	50	0.41	0.4	8.2
WallY2_S6	Wall-hung toilet bowlx5 (135 kg)	27 m²	55	0.43	0.4	9.46
WallX2_S6	Screen (25 kg)	27 m²	50.93	0.41	0.4	8.35252
WallY1_S6		27 m²	50	0.43	0.4	8.6
WallX1_S7	Signboard (75 kg)	27 m²	52.7	0.45	0.4	9.486
WallY2_S7		27 m²	50	0.46	0.4	9.2
WallX2_S7	Embedded bookshelves (150 kg)	27 m²	55.5	0.45	0.4	9.99
WallY1_S7		27 m²	50	0.46	0.4	9.2
WallX1_S8	Embedded bookshelves (150 kg)	27 m²	55.5	0.55	0.4	12.21
WallY2_S8		27 m²	50	0.57	0.4	11.4
WallX2_S8	Wall-hung toilet bowlx5 (135 kg)	27 m²	55	0.55	0.4	12.1
WallY1_S8		27 m²	50	0.57	0.4	11.4

Figure B.2. Schedule in Revit Interface for Calculation of Seismic Design Force of Drywalls in Case I

Seismic Force

< SEISMIC FORCE FOR CASE II >

A	B	C	D	E	F	G
Wall Name	Comments(Hanging Equipments)	Area	Unit Weight(kg)	Acceleration (g)	ap.Ax/(Rp/Ip)	Seismic Design Force
WallX1_S1		27 m²	50	0.35	0.4	7
WallX2_S1	Signboards (75 kg)	27 m²	53	0.35	0.4	7.38
WallY1_S1	Signboards (75 kgx2)	27 m²	56	0.37	0.4	8.22
WallY2_S1	Screen (25 kg)	27 m²	51	0.37	0.4	7.5
WallY2_S2		27 m²	50	0.38	0.4	7.6
WallX1_S2		27 m²	50	0.37	0.4	7.4
WallY1_S2	Wall-hang toilet bowl x5 (135 kg)	27 m²	55	0.38	0.4	10.45
WallX2_S2	Signboards (75 kg)	27 m²	53	0.37	0.4	7.8
WallX2_S3		27 m²	50	0.41	0.4	8.2
WallY1_S3	Embedded Bookshelves (150 kg)	27 m²	56	0.45	0.4	9.99
WallX1_S3	Screen (25 kg)	27 m²	51	0.41	0.4	8.34
WallY2_S3		27 m²	50	0.45	0.4	9
WallX1_S4	Board (50 kg)	27 m²	52	0.52	0.4	10.78
WallY2_S4		27 m²	50	0.5	0.4	10
WallX2_S4	Wall-hang toilet bowl x5 (135 kg)	27 m²	56	0.53	0.4	11.79
WallY1_S4	Screen (25 kg)	27 m²	51	0.51	0.4	10.38
WallY1_S5		27 m²	50	0.59	0.4	11.8
WallX2_S5		27 m²	50	0.56	0.4	11.2
WallY2_S5	Embedded Bookshelves (150 kg)	27 m²	56	0.59	0.4	13.22
WallX1_S5		27 m²	50	0.57	0.4	11.4
WallX1_S6	Signboards (75 kg)	27 m²	53	0.61	0.4	12.88
WallY2_S6		27 m²	50	0.64	0.4	12.8
WallX2_S6	Wall-hang toilet bowl x5 (135 kg)	27 m²	55	0.61	0.4	13.42
WallY1_S6		27 m²	50	0.64	0.4	12.8
WallX1_S7		27 m²	50	0.67	0.4	13.4
WallY2_S7	Signboards (75 kgx2)	27 m²	56	0.69	0.4	15.46
WallX2_S7	Wall-hang toilet bowl x5 (135 kg)	27 m²	55	0.67	0.4	14.74
WallY1_S7	Board (50 kg)	27 m²	52	0.69	0.4	14.31
WallX1_S8	Screen (25 kg)	27 m²	51	0.82	0.4	16.7
WallY2_S8	Embedded Bookshelves (150 kg)	27 m²	56	0.85	0.4	19.04
WallX2_S8	Wall-hang toilet bowl x5 (135 kg)	27 m²	55	0.82	0.4	18.04
WallY1_S8		27 m²	50	0.85	0.4	17

Figure B.3. Schedule in Revit Interface for Calculation of Seismic Design Force of Drywalls in Case II

Seismic Force

< SEISMIC FORCE FOR CASE III >

A	B	C	D	E	F	G
Wall Name	Comments(Hanging Equipments)	Area	Unit Weight(kg)	Acceleration (g)	ap.Ax/(Rp/Ip)	Seismic Design Force
WallX1_S1		25 m²	50	0.37	0.4	7.4
WallY1_S1		25 m²	50	0.37	0.4	7.4
WallX2_S1	Signboard (75 kg)	25 m²	53	0.37	0.4	7.844
WallY2_S1	Screen (25 kg)	25 m²	51	0.37	0.4	7.548
WallX1_S2	Signboard (75 kg)	25 m²	53	0.37	0.4	7.844
WallY2_S2		25 m²	50	0.4	0.4	8
WallX2_S2	Wall-hung toilet bowlx5(135 kg)	25 m²	55.4	0.37	0.4	8.1992
WallY1_S2		25 m²	50	0.4	0.4	8
WallX1_S3	Embedded bookshelves (150 kg)	25 m²	56	0.43	0.4	9.632
WallY2_S3		25 m²	50	0.45	0.4	9
WallX2_S3	Wall-hung toilet bowlx5 (135 kg)	25 m²	55.4	0.43	0.4	9.5288
WallY1_S3	Screen (25 kg)	25 m²	51	0.45	0.4	9.18
WallX1_S4		25 m²	50	0.5	0.4	10
WallY2_S4		25 m²	50	0.51	0.4	10.2
WallX2_S4	Wall-hung toilet bowlx5(135 kg)	25 m²	55.4	0.51	0.4	11.3016
WallY1_S4		25 m²	50	0.5	0.4	10
WallX1_S5	Embedded bookshelves (150 kg)	25 m²	56	0.57	0.4	12.768
WallY2_S5		25 m²	50	0.6	0.4	12
WallX2_S5	Wall-hung toilet bowlx5 (135 kg)	25 m²	55.4	0.57	0.4	12.6312
WallY1_S5		25 m²	50	0.6	0.4	12
WallY1_S6		25 m²	50	0.66	0.4	13.2
WallX2_S6	Wall-hung toilet bowlx5 (135 kg)	25 m²	55.4	0.62	0.4	13.7392
WallY2_S6		25 m²	50	0.66	0.4	13.2
WallX1_S6		25 m²	50	0.62	0.4	12.4
WallX1_S7		25 m²	50	0.71	0.4	14.2
WallY2_S7	Blackboard (50 kg)	25 m²	52	0.71	0.4	14.768
WallX2_S7	Wall-hung toilet bowlx5 (135 kg)	25 m²	55.4	0.71	0.4	15.7336
WallY1_S7		25 m²	50	0.71	0.4	14.2
WallX1_S8	Signboard (75 kg)	25 m²	53	0.81	0.4	17.172
WallY2_S8		25 m²	50	0.84	0.4	16.8
WallX2_S8	Wall-hung toilet bowlx5 (135 kg)	25 m²	55.4	0.81	0.4	17.9496
WallY1_S8	Screen (25 kg)	25 m²	51	0.84	0.4	17.136

Figure B.4. Schedule in Revit Interface for Calculation of Seismic Design Force of Drywalls in Case III