

Universidade do Minho
Escola de Engenharia

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BIM Aided Structural Analysis of Steel Buildings

**BIM Aided Structural Analysis
of Steel Buildings**
Juan Montenegro

BIM A+ European Master in
Building Information Modelling

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European Master in
Building Information Modelling

Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of:
Prof. Maria Isabel Valente, Ph.D.



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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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RESUMO

Esta dissertação aborda o comportamento das ligações em edifícios de estrutura metálica desenvolvendo diferentes níveis de análise que são facilitados pela utilização de vários programas de cálculo estrutural com diferentes capacidades. Atualmente, os projetos de estruturas metálicas são desenvolvidos considerando ligações rígidas ou ligações articuladas, apesar de diversos estudos terem já revelado que a maior parte das ligações apresenta um comportamento semi-rígido. A crescente disponibilidade de software BIM permite fornecer ferramentas necessárias para realizar análises mais refinadas. Tendo em consideração a importância das ligações no comportamento na estrutura, é proposta uma nova metodologia para realizar análises estruturais mais precisas, utilizando as ferramentas BIM como elo de ligação entre as fases de análise, projeto e fabrico.

O ponto de partida do processo é o modelo estrutural, no qual as ligações são consideradas como rígidas ou articuladas. O modelo é então exportado para o software Tekla Structures usando IFC e plug-ins para detalhar as ligações. O Tekla Structures BIM Link é usado para sincronizar o cálculo das ligações metálicas com o software IdeaStatiCa, a fim de realizar a sua verificação de segurança estrutural e avaliar a respetiva rigidez. Considerando os resultados obtidos no IdeaStatiCa, modificam-se as características das ligações entre nós do pórtico analisada, no software Etabs e, com base nos novos esforços obtidos, é realizado um redimensionamento da estrutura. Do software de análise estrutural são obtidos resultados como forças internas, modos de vibração e desvios, e do software BIM são coletados resultados como levantamento de quantidades.

A metodologia desenvolvida é aplicada à análise de edifícios industriais metálicos com pórticos resistentes a momentos fletores no plano do pórtico e contraventamentos concêntricos na direção perpendicular. Os resultados são confrontados com os que foram obtidos a partir de uma análise sem considerar a rigidez das ligações e de uma análise considerando a rigidez da junta conforme prescrito na EN 1993-1-8:2005 e AISC 360-16. As considerações finais e recomendações sobre o processo de utilização do BIM são apresentadas nas conclusões.

Palavras chave: Análise Estrutural, BIM no Projeto de Estruturas Metálicas, Edifícios Industriais, Ligações, Ligações Semi-rígidas.

ABSTRACT

This dissertation addresses the behaviour of connections in steel framed buildings by developing different levels of analysis that are facilitated by the use of several structural software with various capabilities. Nowadays, structural design is performed by considering either rigid or pinned joints, despite several studies have revealed that many joints present a semi-rigid behaviour. The increasing availability of BIM software provides the tools needed to perform a more refined analysis. Taking into account the importance of the joints behaviour on the structure, a new methodology is proposed to perform more accurate structural analysis with the help of BIM as the link between analysis, design and fabrication phases.

The starting point of the process is the structural model, in which the connections are considered as rigid or pinned. The model is then exported to Tekla Structures by using IFC and plug-ins to detail the connections. Tekla Structures BIM Link is used to synchronize the calculation of the metallic connections with IdeaStatiCa, in order to perform safety verifications and assess their stiffness. Considering the results obtained in IdeaStatiCa, the frame partial fixity springs are modified in Etabs and a redesign of the structure is performed. From the structural analysis software, results like internal forces, modes of vibrations and drifts are obtained, and from the BIM software results like quantity take-off are collected.

The developed methodology is applied to the analysis of industrial steel buildings with moment resisting frames in the frame plane and concentric bracings in the perpendicular direction. The results are confronted with those obtained from an analysis without the consideration of semi-rigid joints and from an analysis considering joint stiffness as prescribed in EN 1993-1-8:2005 and AISC 360-16. Final remarks and recommendations about the process of using BIM are presented in the conclusions.

Keywords: BIM in Structural Steel Design, Industrial Steel Buildings, Refined Structural Analysis, Steel connections, Semi-rigid joints.

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1. INTRODUCTION

1.1. General remarks

Nowadays, steel is the option for numerous structures, thanks to many advantages offered by this material, which include its reliability, its high-strength to volume ratio, its ability to adapt to nearly any architectural form or the availability of standardized parts. When analysing structural steel buildings, some assumptions are made in the design phase. For example, beam-to-column connections are assumed either fully fixed or perfectly pinned. This is a simplification that may include some level of error in the estimation of the structure's global behaviour regarding structural drift or frame stability and moment distribution. In reality, no connection behaves like truly fixed or pinned since it possesses some rotational stiffness. Therefore, a more accurate analysis of the structure can be achieved if it includes the semi-rigid behaviour of the connections.

BIM has contributed to increase the digitalization of processes in the AEC industry, seeking more efficiency and revenues for the industry. Nevertheless, the structural engineering sector is perhaps not yet fully engaged to the BIM methodology. One reason might be its low exposition to shareholders and contractors. Most of the structural design offices in Latin America are still in BIM Level 0 except for Chile, which was the first country to officially adopt BIM in public projects and design offices work with BIM level 1 (Arellano, K. et al., 2021). In Europe, most offices have reached BIM level 1, with the exceptions of UK, Germany and France where BIM was introduced earlier and therefore the most common BIM maturity level is 2 (O'Malley, A., 2021).

Introducing BIM into the design phase for structural analysis might be beneficial in terms of time efficiency and improved structural analysis. BIM software can work together with structural software to model the connections and obtain its properties, providing more refined analysis, where the stiffness of the connections is considered. This approach might take more work and time, but it is countered with the fact that BIM models provide shop drawings and quantity estimations more accurately than any structural analysis software and time is regained in these stages.

1.2. Objectives

This dissertation proposes to deliver a practical upgrading of work processes in a structural design office. This upgrade is triggered by upcoming BIM challenges and will focus on implementing a BIM innovation that might increase the work productivity. A new methodology for structural analysis is proposed where the stiffness of the connections is considered in the global analysis of the building. The BIM software is associated with a specific connection software and a structural analysis software and the interoperability between these tools is the central part of the process. This will facilitate the coordination and collaboration at design and drawings production stages and create a BIM model suitable to be exported to other parties of the project. The case study of an industrial steel building is prepared, in order to assess the adequacy of the methodology. In addition, the interoperability of software involved in the workflow is demonstrated.

1.3. Activities and organization

The dissertation is structured in 6 chapters. The first chapter comprises an introduction to the work developed and it opens with the problem and subject of research. Secondly, the purpose and objectives of the research are described and lastly the methods of research are clarified.

The second chapter contains a literature review about the topics considered crucial to support the development of the work. It focuses on the use of building information modelling in the scope of structural design.

The third chapter corresponds to a literature review regarding structural analysis considering semi rigid joints. It gives insight into the relevance of the connections in the global behaviour of the structure. Moreover, it sets the framework for considering semi-rigid connections and taking into account the dispositions of European and U.S.A. standards.

The fourth chapter, “BIM Aided Structural Analysis Methodology”, details the steps of the proposed methodology. It clarifies how to use the various software and establishes the interoperability between them considering IFC and plug-ins. A description of how and why each software forms a part of the workflow to achieve the goal is given.

The fifth chapter is dedicated to apply the developed methodology to a case study. The selected case study is an industrial steel building with concentrically bracings in one direction and moment frames in the other direction. The proposed case study was chosen to put in evidence the effect of stiffness in pinned joints and moment joints. The analysis includes the use of the traditional approach, the application of the new methodology here proposed and the comparison between both. Furthermore, indicators like time expend and structure weight are assessed in order to give a broader insight of how BIM aided structural analysis is beneficial.

Lastly, the conclusions are given in chapter six. The results of the developed work are discussed, and further developments for achieving a higher level of interoperability, thus increasing the productivity in the design stage are indicated.

2. BIM BACKGROUND

Building Information Modelling (BIM) was initially introduced by UK in the 80's of the 20th century to describe the new data-rich models, in comparison to the typical 2D or 3D designs. In the AEC industry there is confusion between what is BIM and what is simply 3D modelling. A three-dimensional model is not BIM unless that model has embedded, meaningful information. Considering that, parts of the BIM process do not need to be three dimensional, and possibly are not. While a three-dimensional model offers a way to convey design intent more clearly and is an excellent tool in the BIM process, it is not BIM in and of itself.

NBIMS defines BIM as “a digital representation of physical and functional characteristics of a facility and a shared knowledge about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” (NBIMS-US, 2017). In its truest, most idealized form, BIM should be part of a project from conception to demolition. BIM should be utilized by all stakeholders in a project, and the information should be shared from one project participant to another with an eventual goal of being passed onto the owner for facilities management. If only some parties utilize BIM, or if those parties do not share the information, the benefits are lost (Mackey, 2017).

BIM is a methodology that changes the way we manage the entire construction production processes. It has been developing in the most industrialized countries, as pivotal factor for the AEC industry. It consists in a collaborative platform, allowing higher efficiency at all stages of a project. BIM results in an integrated model with graphical design and non-graphical information, shared between the different stakeholders. BIM has contributed to increase the digitalization of the AEC processes by addressing its low productivity growth over time and seeking more efficiency and revenues for the industry (Mihindu and Arayici, 2008)

The application of BIM enhances collaborative processes and optimizes actions with greater value for the whole life cycle of a project. “It gives the possibility to the top management, the necessary databases and resources to make efficient strategic decisions, for the operation and maintenance phases of a facility” (Caputi and Ferrari, 2014)

2.1. BIM for structural engineering

BIM is a 3D model-based process that helps structural professionals to design, detail, document, and fabricate structural systems. BIM enables project teams to work more collaboratively, by helping to optimize designs, improve accuracy, and connect design to fabrication, in order to deliver projects faster and more efficiently. Using BIM, structural engineers can make more informed design decisions, automate construction documentation, and produce more accurate, constructible designs (Autodesk, 2022).

BIM helps structural engineers to optimize and automate designs, reduce errors and risk, and improve accuracy and constructability, while improving overall project delivery.

2.1.1. BIM Importance in structural design

The importance of BIM in structural design relies on the many features that a BIM based design offers and the versatility of applications. The digital models produced by structural engineers can be coupled with downstream activities, for manufacturing and assembly of structural elements as well as identifying coordination problems between structural elements and those of other disciplines. BIM can be a part of an effective solution for structural engineers in monitoring the health and life cycle performance of structural elements, seismic retrofitting optimization, and risk assessment of structures. Other applications of BIM for structural engineering include increasing its efficiency in modeling complex geometrical structures, generating shop drawings, and designing temporary elements and formwork. With the above in mind, structural design/analysis must be treated as one of the main areas of application for BIM (Vilutiene et al.,2019).

According to the report *Shaping the Future of Construction: A Breakthrough in Mindset and Technology* by the World Economic Forum, where new technologies are identified together with their possible impact on the industry (see Figure 1), Integrated BIM is found to be the most likely technology with an extremely high impact (World Economic Forum, 2016)

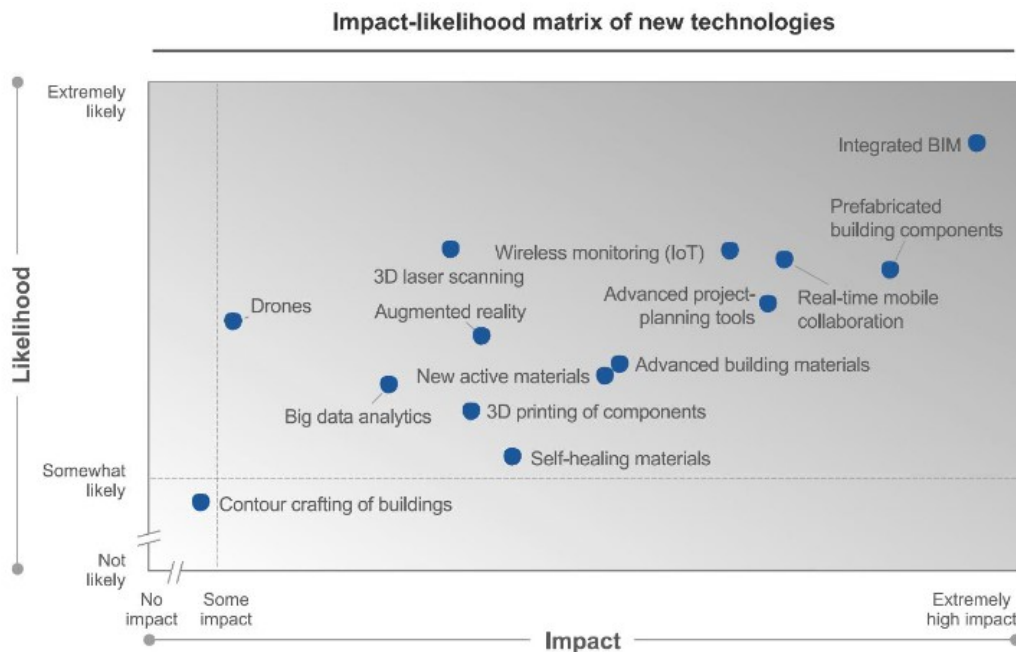


Figure 1 – Future impact and likelihood of technologies (World Economic Forum, 2016)

2.1.2. BIM Advantages in structural design

Structural designers confront many advantages of BIM in various forms, as the model can be consistently updated for achieving integrated design. BIM also changes the form of how one manages and see the items. It increases the impact on building design, structural design, and engineering analysis. BIM makes possible the reduction in design efforts, minimizes errors and changes, develops cost-effective designs and increases production quality. It ensures better results, both in design and construction (AutodeskAEC, 2017).

The following advantages of implementing BIM in structural design were identified by a review done by G. Ozturk and O. Eraslan from a compilation of 86 papers. In summary, quality, collaboration, scheduling, communication, estimation, lean efforts, and resource allocation are listed as major advantages of BIM (Ozturk and Eraslan, 2018)

Clash detection and parametric change management

One of the usual by-products of the reduction in recurring data entry made possible under the BIM structure is a decrease in the errors introduced by design alterations. When a customer requires a completed set of documents to hit a delivery deadline, it's easy to envision small computational errors coming up - even in a single model; errors, time loss, and loss of status as well. BIM can be used to solve this problem by clash detection ability and by means of parametric change management capabilities.

Effective collaboration

The application of BIM in the structural engineering office provides great benefits. Regardless of how projects' designer favor to share design information, even on paper, BIM at the engineering company makes it easier to evaluate late alter and quickly return the data to the designer for examination.

Engineers also seem to understand that, if all members of a project team utilize information modeling, significant collaboration is immediately available. Beyond the simple act of combining models to visualize the interaction between disciplines, models from other project team members can be incorporated and used by the other disciplines.

Integrated database

BIM model provides integrated database used as the foundation of knowledge of the building and the construction works which make better the accuracy and quickness of cost approximation by automation of quantity calculation therefore make better productivity.

Double-check calculations

Structural analysis software is seen as a time saver by most of the professional engineers, contractors and architect. BIM can be used to double-check calculations as well as do difficult functions with increased precision. Building codes are pre-programmed, and values such a load limits and deflection are produced automatically, giving you time for other task of the project.

Estimated and material accuracy

Creating a comprehensive, structural model that is rich with information allows structural engineers to obtain correct material quantities to create more economical bids with much lower contingencies. Besides giving structural engineering company a competitive edge for securing business, constructible models allow materials to be sequenced and prearranged with confidence to decrease material waste and the cost of fixing error come across at the job site.

Recognize early problems

Virtual design and construction with BIM create the potential to recognize problems earlier in the construction process. Most of all users see this as an important advantage, mostly contractors. More experienced users recognize its value compared to others.

Improved communication

BIM gives a source of comprehensive combined information that becomes a trusted repository of combined correct data and measurements to make sure consistency, as every trade constructs their own models. The entire project team profits from speedier, easy communication and enhanced organization.

Reduced waste

Information is coherent with the use of BIM. Designers can then make well-informed conclusions that can help decrease the environmental effect of buildings, in which factory built assemblies can be used. In that case the information can be managed better and factors such as waste- on-site can significantly be reduced.

2.1.3. BIM Benefits

The more obvious benefits, such as enhanced and earlier coordination, are relatively well understood. There is also some level of acceptance that modeling in three dimensions, with components that contain some amount of embedded data, is inherently favorable and more efficient than the traditional two-dimensional approach.

Furthermore, if providing these models would mean more streamlined construction translating into shortened construction schedules, this could also offer an opportunity for designers to negotiate more time for design. Alternatively, designers could potentially negotiate additional fees for providing a design that presents more advantages than a traditional one (Mackey, 2017).

Design flexibility

With time and budget independence afforded by the use of BIM within the project, engineers are open to think about such alternatives – the type of job for which they have educated. Additional flexibility also leads to more content clients.

Better project outcomes

Almost half of the construction companies claim that BIM's influence on the general project result is a high advantage. Companies, which are less experienced in BIM, consider this as their highest advantage, while expert companies rank it slightly lower.

Reduced rework

Fixing problems early means fewer issues in the plans and in the end fewer hassles in the field. A bulk of contractors (57%) sees the promise of BIM to decrease rework as a huge benefit. This is the top –

ranked benefit reported by expert users (77%), in comparison to fewer beginners that see it in other ways. (23%).

Better marketing

BIM offers opportunity for companies in the construction environment. As more customers start to need BIM on jobs, construction members require having BIM skills to capture that business. On the other side, companies can also present the technology to new clients who do not require BIM and use this as a marketing aspect to get an opportunity in their bid to get a job.

Greater efficiency

For structural engineering team whose responsibility long has relied on logical models that predict occurrence, the instantaneous promise of BIM and associated tools and technology can lead to a better efficiency. Structural engineering team must be particularly proficient at responding to late-stage alteration that requires compromise because it's mostly too late or too costly to alter physical design. One of the main issues with last-minute modification to a project is the necessity to re-enter information for those changes. By getting rid of the need to put aside large amounts of time for the tiresome redrafting and co-ordination of foreseeable changes, that time can be used for a better purpose: engineering and analytic, which add far better value to a given project.

2.1.4. Future advances

In the near future, optimistically speaking, the most evident change that will impact the structural engineering industry is that building information models and analytical models will be fully integrated or perhaps even one in the same (Mackey,2017). The interoperability will be improving with each release of the various software packages. The time spent creating, modifying, updating, and managing two independent models is a significant line item in a project budget, so there is much to be gained as these two modeling efforts merge. However, this is not necessarily something that structural engineers can control; this is dependent upon future advancements in technology.

Looking at what structural engineers can control, the next step is more likely finding ways to improve upon internal workflows. This could be achieved by more completely and more efficiently utilizing the data embedded in the information models that are already being created. By removing the unintelligence of a simple drawing and replacing it with layers of metadata, information about a structure can be exchanged more efficiently and accurately across the entire design and construction team. Utilizing this metadata is key in taking the next step with BIM.

2.2. BIM maturity

In the introduction, the BIM maturity level of Europe and Latin America was mentioned. In order to have a good comprehension of what these levels mean, following there is small description of BIM maturity levels. BIM maturity levels define the technological progress achieved in the AEC sector according to the degree of collaboration and information sharing between the different stakeholders involved in a project.

2.2.1. Levels in PAS 1192

Starting from a basic level where there is no collaboration to carry out the work activities and going up to the last level characterized by seamless integration of information and the use of cloud platforms and BIM models (see Figure 2). PAS 1192-2 introduces 4 levels of digital maturity (BibLus, 2019):

- L0 – low collaboration – you work in 2 dimensions with Computer Aided Design (CAD) software or on paperwork;
- L1 – partial collaboration – working in 2 or 3 dimensions 3D CAD Software with digital files;
- L2 – full collaboration – works in 3 dimensions
- L3 – full integration.

BIM level 0 (low collaboration)

It is the lowest step of the information generation process, where there is practically no cooperation. At this stage, the production and sharing of the information takes place with non-interoperable, paper-based documents: CAD drawings are used, but the information of the model is not shared. Nowadays, the majority of technicians is at this stage: although they use BIM oriented software, they exchange paper-based information that cannot communicate between one another.

BIM level 1 (partial collaboration)

Many studios and companies are adapting their work at this stage. A Common Data Environment (CDE) is used in this case. A CDE is an online shared repository where all the data of the project are collected and managed. In other words, BIM level 1 focuses on the transition from CAD information to 2D and 3D one. Despite the presence of a common data environment, the generated models are not distributed among the different stakeholders.

This level is about information management through a standardization of the model among team members.

BIM level 2 (full collaboration)

This level focuses on how the information is shared among the various members of the project. At this stage, two new dimensions of the project are introduced: the 4D, time management and the 5D, calculation of the budget. Although the collaborative working is at the center of the BIM level 2, it is not necessary that all the team members operate on the same CAD 3D models. In fact, every member can use a distinct CAD model in a common file type (an IFC file for instance, used to exchange BIM data) that contains all the design information. In this way, all the stakeholders involved in the project have an overview of all the available information and can modify it accordingly. This allows the full collaboration among the numerous parts of the project and the creation of a unified BIM model. To reach this goal, the CAD software that every member uses should export in common file types such as IFC file, COBie file etc.

To sum up, at this stage all the members of the team work in a coordinated way to obtain a federate model that maintains the specific characteristics of every discipline of designing.

BIM level 3 (full integration)

In this level, the main purpose of is to obtain a full integration of information in a cloud-based environment. This is possible using a common shared model that will be available to all the stakeholders of the project who can add or modify their own information. This model in IFC format, is the milestone that can be shared and preserved in a cloud, so that all the agents can have access to the same information. The project team verifies in real time the effects of the single action on the model. In this way the entire life cycle of a building, from its designing to its construction and maintenance can be managed.

This is a future implementation but the majority of AEC markets all over the world keep focusing on support, formation and education to obtain BIM maturity level 2 capacities.

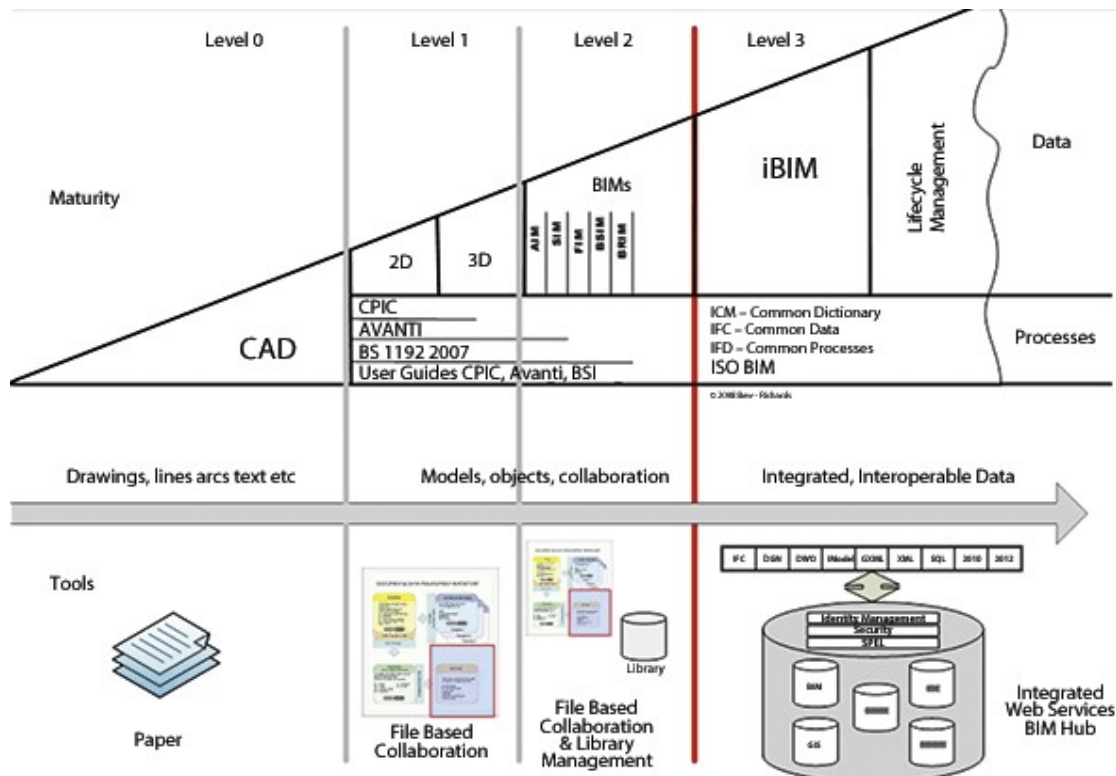


Figure 2 – UK maturity Model (Bew & Richards, 2008)

2.2.2. Levels in ISO 19650

With the publication of ISO 19650 (parts 1 and 2) in 2018, new regulatory scenarios have emerged at the international, EU, and individual State levels. Currently, this standard is the primary reference for all other existing standards. Specifically, ISO 19650-1:2018 re-proposes and actualizes the concept of BIM Maturity, with a schematization (see Figure 3) similar to the Bew-Richards triangle (see Figure 2). It essentially identifies 3 stages of BIM maturity (BibLus,2019):

- BIM STAGE 1 in which 2D CAD deliverables and 3D BIM models (information models) are combined, meeting national regulatory requirements, for project management
- BIM STAGE 2 in which the information models of the individual disciplines (structural, architectural, MEP systems, etc.), federated and meet international standards ISO 19650, ensuring the integrated management of the construction project
- BIM STAGE 3 in which the structured database systems of the informative models, immediately interrogable, allow to impose the OPEN BIM as a project management system and of its subsequent commissioning.

In addition, activities of Asset management are envisaged, understood as a real estate asset, i.e. the system of real and/or virtual objects of a building.

Progressing from Stage 1 to 3, there is an increasing integration of data both at technological and information level. In particular, Stage 2 data sharing is based on the exchange of models and files, while Stage 3 moves towards model management through structured platforms that enable the optimization of all BIM processes and direct model interrogation.

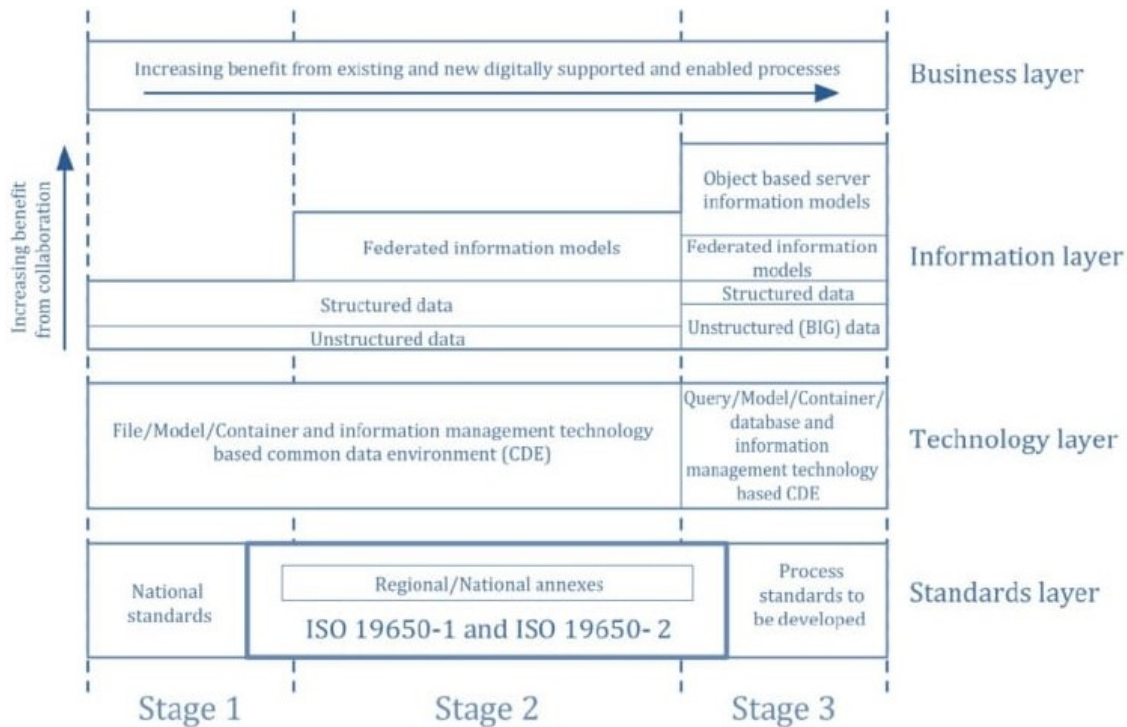


Figure 3 – ISO BIM maturity levels (ISO 19650, 2018)

2.3. BIM implementation

Literature shows that BIM can be implemented with success in the design practice from professionals that have the right expertise. BIM creates easier workflows and modelling, saving time and money. The requirement of skilled people is a must to assure an effective BIM process. It has been identified that applying BIM, produces higher income for projects. Economies of scale results in better prices for BIM costs. (Czmoch and Pękala, 2014)

BIM adoption evaluation can be done at a “Project” or “Organization” level, based on workflows and technologies applied within an organization (Dakhil et al., 2015). BIM capacity assessment evaluation are also important towards the “Individual” competencies, being the base for the organizational functioning.

Implementing BIM methodology within a firm is a radical and innovative change. Several data and Vendor’s information showed that a lot of software offer BIM solutions with higher costs. These costs may be relevant at the beginning, but the future outcomes of the project justify the initial investment, with higher return on investments (ROI).

BIM can be implemented in the following structural related cases (Azhar, 2011):

- 3D modelling enriched with graphical and non-graphical information, virtual visualization and render simulation.
- Facilitation for fabrication and shop drawings.
- Use of the model for analysis and verification for the different disciplines, structural analysis and detailing, energy modelling, sustainability evaluations, fire safety, etc.
- Cost’s estimation: BIM methodology allows to have automated quantity analysis and costs estimations for every update of the model.
- Time scheduling of the construction works for coordination of materials ordering, fabrications (cast in place or in situ, assembling etc.) and delivery scheduling for all the building elements.
- Clash detections (conflicts, incompatibilities), verifying elements not intersecting, doubling, or distance criteria between relevant components.
- Sustainability analysis for green certification like LEED, carbon footprint evaluation etc.
- Dismantling procedures and recycling of the building elements for future uses.
- Forensic analysis, like evacuation plans, failure and so on

2.4. BIM challenges

The research BIM Latin America and Caribbean 2020, conducted by the Inter-American Development Bank (IDB) in order to offer a broad view of the state of BIM in the region, found the challenges to implement BIM (see Figure 4), while in Europe the challenges were found in the analytical report “Digitalization in the Construction Sector” (see Figure 5) published by the European Construction Sector Observatory (ECSO).

2.4.1. In Latin American

The main challenge is the investment costs. The reason is because most of the software are developed either in Europe or USA where economies are bigger and as the purchase cost of a BIM software is high and might be accessible only to big design offices. Additionally, these software require more powerful hardware. Secondly, the next challenge is the low demand of BIM models. In Latin America BIM is not mandatory for public projects therefor the demand fall on the private sector which is still not engaged with the BIM approach. Finally, the two last challenges are lack of human talent and lack of education. In a traditional design approach, it is not necessary to have a master or extra courses, on the contrary, for BIM special training is necessary (IDB, 2020).

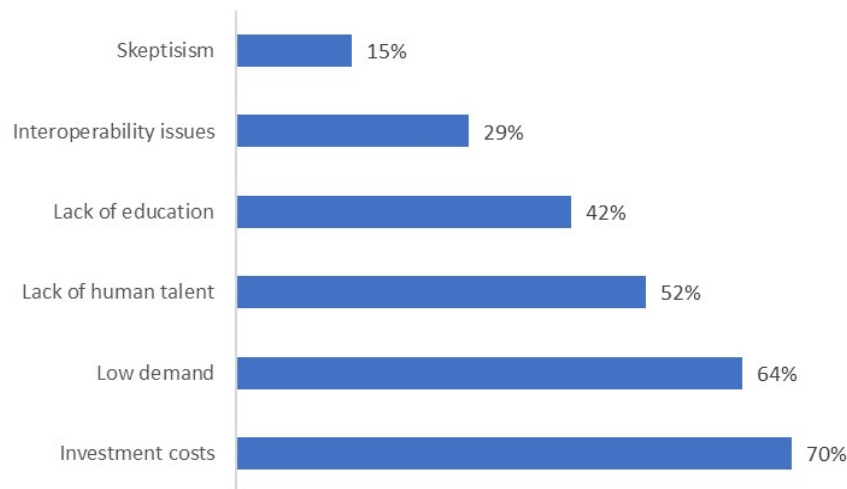


Figure 4 – Principal BIM implementation challenges in Latin America

2.4.2. In Europe

The analysis shows that the three main factors hindering the digitalisation of the EU construction sector are the lack of a skilled workforce, the lack of awareness and understanding of digital technologies and the cost of equipment and software. Additionally, there is a high concern about the legal framework.



Figure 5 – Principal BIM implementation challenges in Europe

2.5. Integrated workflows

Workflows instruct how BIM processes should be implemented within an organization or a project. BIM Dictionary describes the “BIM Workflows” as “successive activities” necessary to perform and deliver milestones. They are aimed to fulfill “strategic/operational objectives” and may be part of larger BIM processes. (BIME, 2019)

In the concept of “integrated workflows” we mean more interoperability between activities, involving software and tools. You may schematize the workflows in continuous steps, connected to each other. Integrated workflows are crucial to deliver BIM products. Most of benefits have been identified in modelling, shop drawings and fabrication, construction, and handover processes.

All disciplines make use of integrated workflows to achieve BIM objectives. Architects start preparing referenced concept models, structural engineers perform code checking and optimize structural modelling. Models may be shared with other BIM modelers, to follow detailing and generate shop drawings. Fabricators or traders make lists for materials ordering and installations. The model, the construction drawings and documentations are coordinated between all disciplines and later applied for the construction works. The model may be updated at any time if modifications are required in the different phases of the project.

The integrated workflows allow for the people involved, to achieve a better communication, reduce the errors onsite, produce and deliver better and coordinated shop drawings, provide accurate estimations, improve scheduling, and in general improve quality (DODGE, 2016). Expectations say that BIM workflows in a globalized world, will also increase the support for teams to work within different locations, by reducing costs and raise production, in small efforts.

The integration of activities in connected workflows, simplifies the modeler and designer’s work. They help to reduce the differences and manual re-working required to go from one step of the project to the other, by automating its connectivity and improving the interoperability. This allows to produce models faster with less errors. It is not a coincidence that the maturity assessment models start from a minimal evaluation for separated processes and increase it towards integrated workflows (Tushaj, 2021).

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3. STRUCTURAL ANALYSIS CONSIDERING SEMI-RIGID JOINTS

The traditional steel frame is widely used in industrial and civil buildings due to its advantages of light weight, uniform material, high strength, good toughness, convenient production, and easy assembly, especially in earthquake-resistant fortified areas and high-rise buildings (Ciutina and Dubina, 2006). In this kind of structural system, beam-column joints often play an important role and are crucial to their ultimate bearing capacity and normal service capacity and even become an extremely important line of defense against structural collapse. In the traditional steel frame structure, some or all of the beam-column joints are manually welded on-site, and high-altitude operations occur from time to time. Although monitoring is required in terms of technology and management, it is difficult to control one by one. It is inevitable and difficult to control the physical and psychological influence of operators, and the onsite environment is not transferred by human will, resulting in the insecurity of welding quality, and the final implementation effect of beam-column joints often deviates from the design. In the 1994 Northridge Earthquake in the United States and the 1995 Hyogoken–Nanbu Earthquake in Japan, on-site inspection of buildings with steel frame structure system revealed that the beam-column joints connected by welding showed various forms of damage or brittle fracture (Li and Huang, 2022).

Based on the reduction or avoidance of on-site welding work, the use of fully assembled steel beam-column joints is a good choice, that is, through reasonable building structure design, the components are connected by high-strength bolts. The strength, stiffness, and seismic performance meet the functional requirements of normal use, the quality of joints can be effectively controlled, and the onsite labor cost can be greatly reduced (Swanson and Leon, 2000). Fully assembled beam-column joint in which the components are basically connected by bolts, the welding between the components is completed in the factory, and the welding is basically eliminated on-site, have shown through experimental research and finite element numerical simulation that the possibility of brittle fracture can be effectively reduced (Zhang and Jiang, 2021). Researches show that the failure mechanism of the structure is good and the seismic performance is excellent, but the connection between the steel beam and the steel column is semi-rigid with bolted connection, and the design can still be uncertain, which needs further in-depth research. (Li and Huang, 2022).

3.1. Relevance of the connections in the global behaviour

The behavior of beam-to-column joints crucially influences the overall frame response (Van Keulen et al., 2003). Connections are known to influence significantly the global and the local behavior of structures in terms of their internal distribution of forces, static displacements, critical loads, and failure loads or failure modes (Geuzaine et al., 2022). Additionally, connections are one of the most significant contributors to decide the ductility and robustness of a steel framed structure. Particularly, moment connections have been used in lateral loading resistant frame design due to their ability to reduce the relative rotation between beams and columns. For example, industrial steel buildings are commonly designed with pinned supports and with strong moment connections (see Figure 6).



Figure 6 – Connections in industrial buildings (Euro-Build, 2008)

Connection stiffness is an important concern in the design of moment frames for seismic resistance. This is because moment frames are inherently flexible systems, and the design of moment frames for seismic resistance is commonly controlled by the building code's requirements to limit inter-storey drift under seismic loading, rather than the requirements to provide minimum strength. If beam-to-column moment connections have significant flexibility, this tends to make the frame as a whole more flexible and requires the use of larger members to control drift to specified levels than would otherwise be required. Nevertheless, in lower seismic design categories, economical structures can be designed that use relatively low-cost, partially restrained moment connections at all beam-to-column connections, mobilizing the entire building frame in seismic resistance (Hamburguer, 2009).

Connection strength is also an important consideration for seismic design. If inelastic frame deformation occurs through yielding of connections, rather than in beams and columns, large concentrated ductility demands may occur in these connections. It is generally preferable to accommodate the inelastic demands on a frame through distributed yielding of the connected members. Nevertheless, some partial-strength connection details have been demonstrated to provide sufficient ductility. An advantage of such connections is that it is often easier to repair damaged connection elements, after an earthquake, than it is to repair yielded or buckled beam and column flanges, which is a common occurrence when plastic hinges form in beams and columns.

3.2. Requirements for dissipative structural behaviour

Based on EN 1998-1:2004 earthquake steel resistant structures shall be designed in accordance with one of the following concepts: Low-dissipative structural behavior; Dissipative structural behavior.

Structures with ductility class low (DCL) shall be designed according to concept a) Low ductility Class. The concept a) is a design approach where the strength assigned to the structure is “sufficiently” large to make the plastic deformation demand from the design earthquake “sufficiently” small. This implies that some detailing rules for ductility can be waived. There is always large uncertainty about the seismic actions. There are chances that the intensity of a real earthquake occurring at the building site is exceeding the design value. If the real earthquake intensity is exceeding the design value, the demand is being larger than assumed for the design (Landolfo, 2014). Because of the previous argument regarding the uncertainties, this concept should be used with caution (EC8 suggests only in case of low seismicity zone).

Structure with ductility class medium (DCM) or high (DCH) shall be designed according to concept b) Dissipative structural behavior.

The design criteria for dissipative structures is the following:

- Structures with dissipative zones shall be designed such that yielding or local buckling or other phenomena due to hysteretic behavior do not affect the overall stability of the structure.
- Dissipative zones shall have adequate ductility and resistance. The resistance shall be verified in accordance with EN 1993-1-1:2005.
- Dissipative zones may be located in the structural members or in the connections (see Figure 7).
- If dissipative zones are located in the structural members, the non-dissipative parts and the connections of the dissipative parts to the rest of the structure shall have sufficient over-strength to allow the development of cyclic yielding in the dissipative parts.
- When dissipative zones are located in the connections, the connected members shall have sufficient over-strength to allow the development of cyclic yielding in the connections.

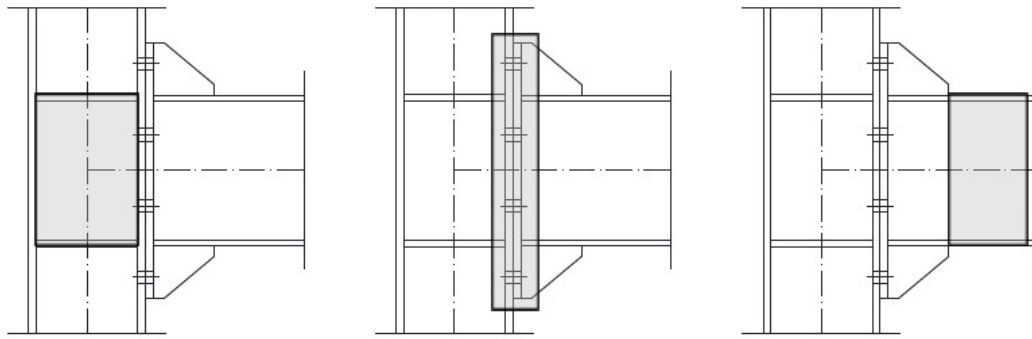


Figure 7 – Dissipative zones in joints (Equaljoints, 2016)

3.3. Design of connections

The following design rules for connections in dissipative zones are prescribed in the chapter 6 Specific rules for steel buildings of EN 1998-1:2004.

- The design of connections shall be such as to limit localization of plastic strains, high residual stresses and prevent fabrication defects.
- Non dissipative connections of dissipative members made by means of full penetration butt welds may be deemed to satisfy the over-strength criterion.
- For fillet weld or bolted non dissipative connections, equation (1) should be satisfied,

$$R_d > 1,1 \gamma_{ov} R_{fy} \quad (1)$$

where R_d is the resistance of the connection in accordance with EN 1993-1-1:2005, R_{fy} is the plastic resistance of the connected dissipative member based on the design yield stress of the material as defined in EN 1993 and γ_{ov} is the over-strength factor, which may be found in the applicable National Annex. The recommended value is $\gamma_{ov} = 1,25$

- Categories B and C of bolted joints in shear, in accordance with section 3.4.1 of EN 1993-1-8:2004 and category E of bolted joints in tension in accordance with section 3.4.2 of EN 1993-1-8:2004, should be used. Shear joints with fitted bolts are also allowed.

- For bolted shear connections, the design shear resistance of the bolts should be higher than 1,2 times the design bearing resistance.
- The adequacy of design should be supported by experimental evidence, whereby strength and ductility of members and their connections under cyclic loading should be supported by experimental evidence, in order to conform to the specific requirements defined for each structural type and structural ductility class. This applies to partial and full strength connections in or adjacent to dissipative zones.
- Experimental evidence may be based on existing data. Otherwise, tests should be performed.

The National Annex may provide reference to complementary rules on acceptable connection design.

3.4. Detailing of connections

If the structure is designed to dissipate energy in the beams, the connections between beams and columns should be designed for the required degree of over-strength, taking into account the resistant moment $M_{pl,Rd}$ and the shear force ($V_{Ed,G} + V_{Ed,M}$).

Dissipative semi-rigid and/or partial strength connections are permitted, provided that all of the following requirements are verified:

- The connections have a rotation capacity consistent with the global deformations;
- Members framing into the connections are demonstrated to be stable at the ultimate limit state.
- The effect of connection deformation on global drift is taken into account using nonlinear static (pushover) global analysis or non-linear time history analysis.

The connection design should be such that the rotation capacity of the plastic hinge region θ_p (see Figure 8): is not less than 35mrad for structures of ductility class DCH and 25mrad for structures of ductility class DCM with $q > 2$. The rotation θ_p is defined by equation (2),

$$\theta_p = \delta / 0,5L \quad (2)$$

where δ is the beam deflection at midspan and L is the beam span.

The rotation capacity of the plastic hinge region θ_p should be ensured under cyclic loading without degradation of strength and stiffness greater than 20%. This requirement is valid independently of the intended location of the dissipative zones.

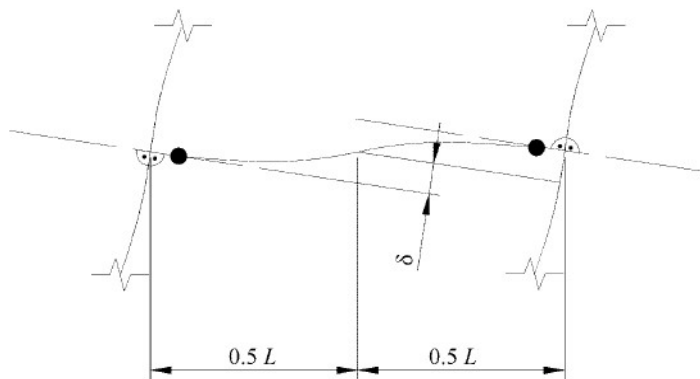


Figure 8 – Plastic hinge region (EN 1998-1, 2004)

In experiments made to assess the rotation capacity θ_p , the column web panel shear resistance should conform to expression $V_{wp,Ed}/V_{wp,Rd} < 1$ and the column web panel shear deformation should not contribute for more than 30% of the plastic rotation capability θ_p .

The column elastic deformation should not be included in the evaluation of θ_p .

When partial strength connections are used, the column capacity design should be derived from the plastic capacity of the connections.

3.5. Classification of connections

Two extreme cases regarding the actual performance of beam-to-column connections have been idealized in traditional analysis and design of steel frame structures. One extreme is known as rigid-joint connection while the other one is referred to as pinned-joint connection. Nevertheless, both of such idealized models do not accurately present the actual behavior since most of the connections demonstrate a semi-rigid behavior. Moreover, non-conservative predictions regarding the structural drift or frame stability could result from such approaches. Thus, real connections in steel frames should be treated as semi-rigid ones. In both specifications for structural steel buildings, American standard AISC 360-16 and European standard EN 1993-1-8:2005, three types of connections are classified: rigid connection, semi-rigid connection and simple connection. However, some differences exist among these two specifications in terms of connection classification schemes.

The fundamental criteria considered in categorizing connections is that the most significant behavioral appearances are exhibited by a moment-rotation curve (see Figure 9). From this point of view, such classifications directly explain strength, stiffness and ductility of connections. For serviceability, deformation and other stiffness-related characteristics of the connections are known to be the prime considerations. Yet, in the case of ultimate limit states, strength parameters would be the major considerations. The maximum moment developed by a connection, M_n , is known as the strength of a connection. Ductility, maximum rotation capacity, θ_u , and energy absorption are believed to be the critical factors for structures located in seismic areas (Faridmehr et al, 2016)

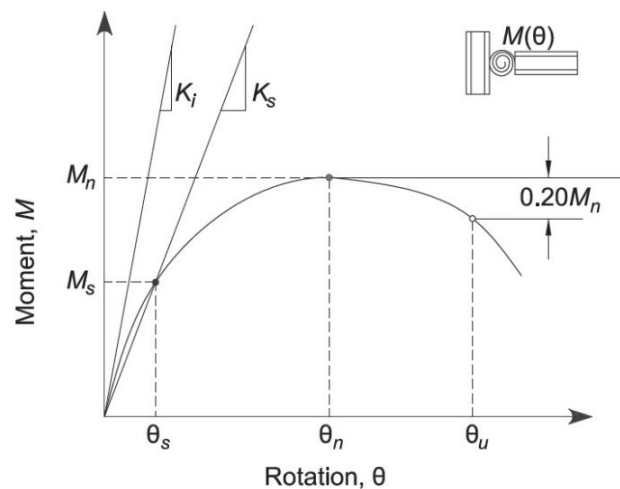


Figure 9 – Moment rotation curve (AISC 360-16, 2016)

3.5.1. AISC 360-16 Classification

Connection classification by AISC specification is conducted through modelling the most significant behavioral characteristics of the connection using a moment-rotation ($M-\theta$) curve. According to AISC guidelines, the $M-\theta$ curve is defined as being a part of the column and beam as well as the connecting components. This is because, in a physical test, the connection rotation is basically identified over a length that takes not only the connecting elements contributions, but also the connected beam and the column shear panel zone. In general, based on AISC specifications, such classifications explain stiffness, strength and ductility of the connections.

The secant stiffness K_s , at service loads is considered a fundamental criteria of the connection stiffness. If $K_s L/EI > 20$, the connection is considered to be fully rigid (FR). If $K_s L/EI < 2$, the connection is classified as simple. The connection stiffness between these two boundaries is categorised as a partially restrained (PR) or semi-rigid connection, and the strength, stiffness and ductility should be taken into account in the analysis.

The maximum moment that can be carried out by a connection is introduced as M_n , as shown (see Figure 10). If the $M-\theta$ curve response does not demonstrate a peak moment, the moment at a rotation of the 0,02 rad is considered the maximum strength of connection (Hsieh and Deierlein, 1991). Connections that convey less than 20% of the plastic moment of the connected beam M_p , at a rotation of 0,02rad, are supposed to have no flexural capacity for analysis. It is worth mentioning that for an FR connection, strength less than the beam strength is anticipated. Yet, it is also probable for a PR connection to provide a moment capacity higher than the connected beam.

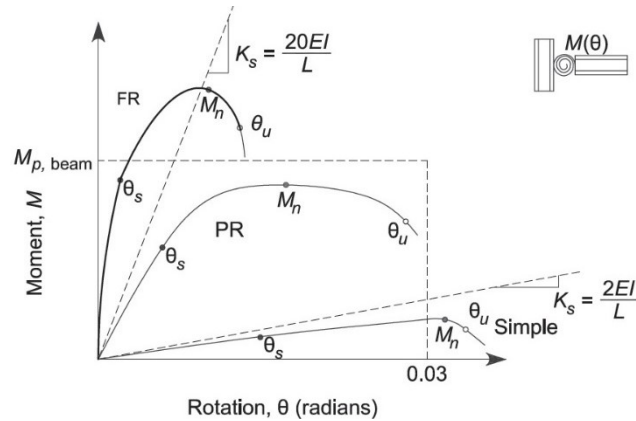


Figure 10 – AISC 360-16 Connection classification (AISC 360-16, 2016)

The required ductility of a connection is a function of its application. For instance, a lower ductility is required for a structure in a low-seismic zone compared to those located in high seismic zones. The structural system plays an important role in rotation ductility requirements for seismic design. Once the connections strength capacity considerably exceeds the plastic moment of the connected beam, the ductility of the whole structure is measured by the beam, and the connection is supposed to remain elastic. The connection may experience severe inelastic deformation where its strength capacity is marginally higher than the plastic moment of the connected beam. However, deformations may concentrate within the connection component if the beam flexural capacity surpasses the connection

strength. According to Figure 9, the rotation capacity, θ_u , identified as the particular point where either the resisting moment has decreased to $0,8M_n$ or the connections has experience deformation beyond $0,03\text{rad}$. This second principle is reliable for connections with no obvious decrease in strength capacity until a very large deformation occurs. An evaluation should be made among the rotation resistance, θ_u and the required rotation strength where a $0,03\text{rad}$ rotation resistance is considered acceptable. This amount is equal to the minimum connection capacity in conformity with seismic provisions for special moment frames (AISC 341-16, 2016)

3.5.2. EN 1993-1-8:2005 Classification

In this specification, connections are classified by their stiffness and strength. A joint may be classified as rigid, nominally pinned or semi-rigid according to its rotational stiffness, by comparing its initial rotational stiffness, $S_{j,\text{ini}}$, with classification boundaries (see Figure 11). Beam-to-column connections categorized as FR are supposed to have adequate rotatinal stiffness to consider analyses based on fully rigid. Zone 1 represents rigid connection and defined as in equation (3),

$$S_{j,\text{ini}} > K_b EI_b / L_b \quad (3)$$

where, K_b is taken as 8 for structures with lateral displacement of frames by at least 80% or as 25 for other frames.

A nominally pinned joint should be capable of transmitting the internal forces, without developing significant moments that might adversely affect the members or the structure as a whole. Connections are considered as nominally pinned, zone 3, if equation (4) is verified.

$$S_{j,\text{ini}} > 0,5 EI_b / L_b \quad (4)$$

The beam-to-column connections that do not address the criteria for FR connections or for simple connections shall be classified as PR or semid-rigid connections, zone 2. PR connections provide an anticipated deformation between connected members, based on the $M-\theta$ curve features of the connections. PR connections are supposed to convey shear forces as well as bending moments.

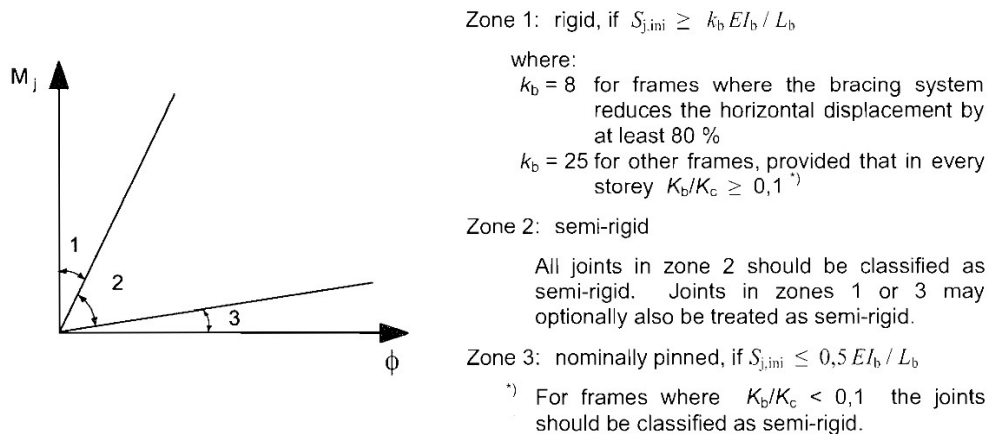


Figure 11 – EN 1993-1-8:2005 Connection classification (EN 1993-1-8:2005, 2005)

A joint may be classified as full-strength, nominally pinned or partial strength by comparing its design moment resistance, M_n , with the design moment resistances of the connected members. A joint is categorized as simple if its design moment resistance, M_n , is not higher than 0,25 times the design moment resistance required for a fully-rigid connection and also addresses the adequate rotation capacity. The design capacity of a fully-rigid connection should not be less than the connected beam. A connection is classified a FR connections $M_n > M_p$.

3.6. Component based finite element method

Component-based finite element method (CBFEM) is a method for the design and code-check of steel joints, anchors and steel members. The steel joints can be created step by step using manufacturing operations (see Figure 12), the model is automatically transferred to the analysis model by the CBFEM and the results according to the code are provided.

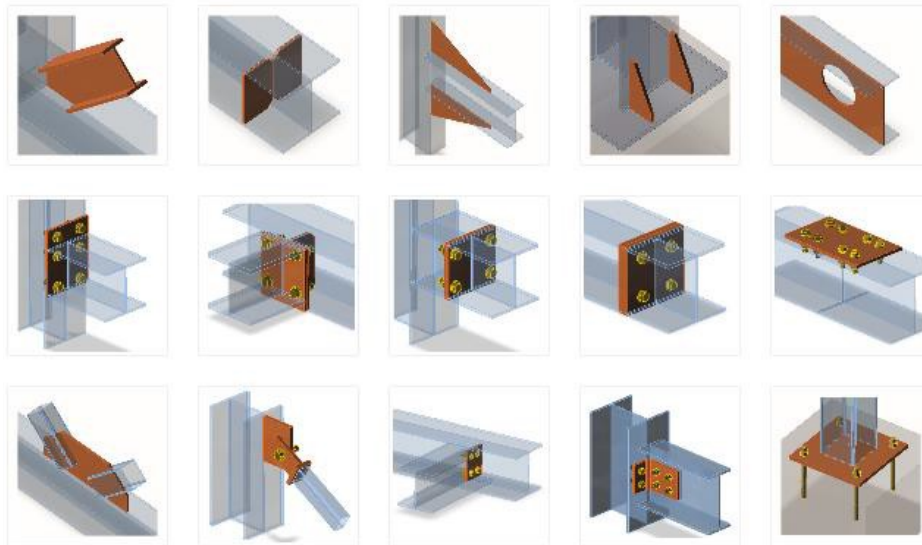


Figure 12 – Predefined manufacturing operations in CBFEM

CBFEM is a synergy of the Component Method (CM) and Finite Element Analysis (FEA) (see Figure 13). This method is based on the idea that most of the verified and very useful parts of the CM should be kept. The weak point of the CM is its generality when analyzing stresses of individual components and is solved by modeling and analysis using the Finite Element Method (FEM).

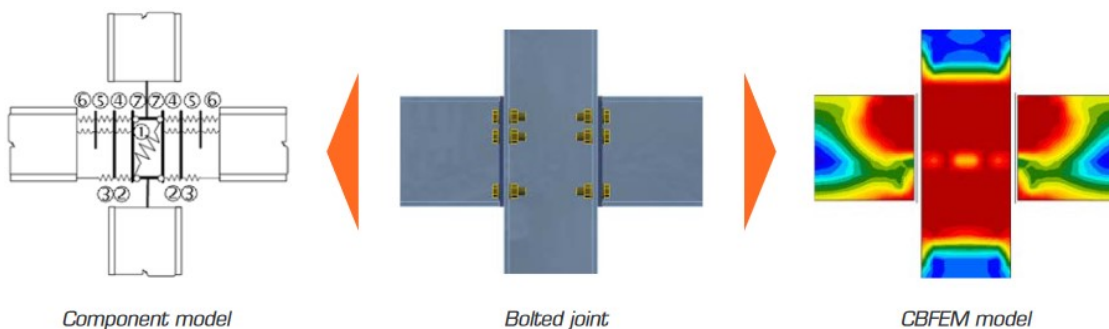


Figure 13 – CBFEM Schematization (IdeaStatiCa, 2022)

CBFEM works using CM and FEM in the following way:

- Joint is divided into components.
- All steel plates are modeled by finite element method assuming ideal elastic-plastic material.
- Bolts and anchors are modeled as nonlinear springs.
- Welds are discretized and modeled as special constraints enabling the stress redistribution due to their plastification.
- Finite element model is used for analyzing internal forces in each of the components.
- Plates are checked for limit plastic strain of 5%.
- Each component is checked according to specific formulas defined by the national code, similarly as when using CM.

The CBFEM approach provides a framework that has been expanded to different types of joint analysis (see Figure 14).

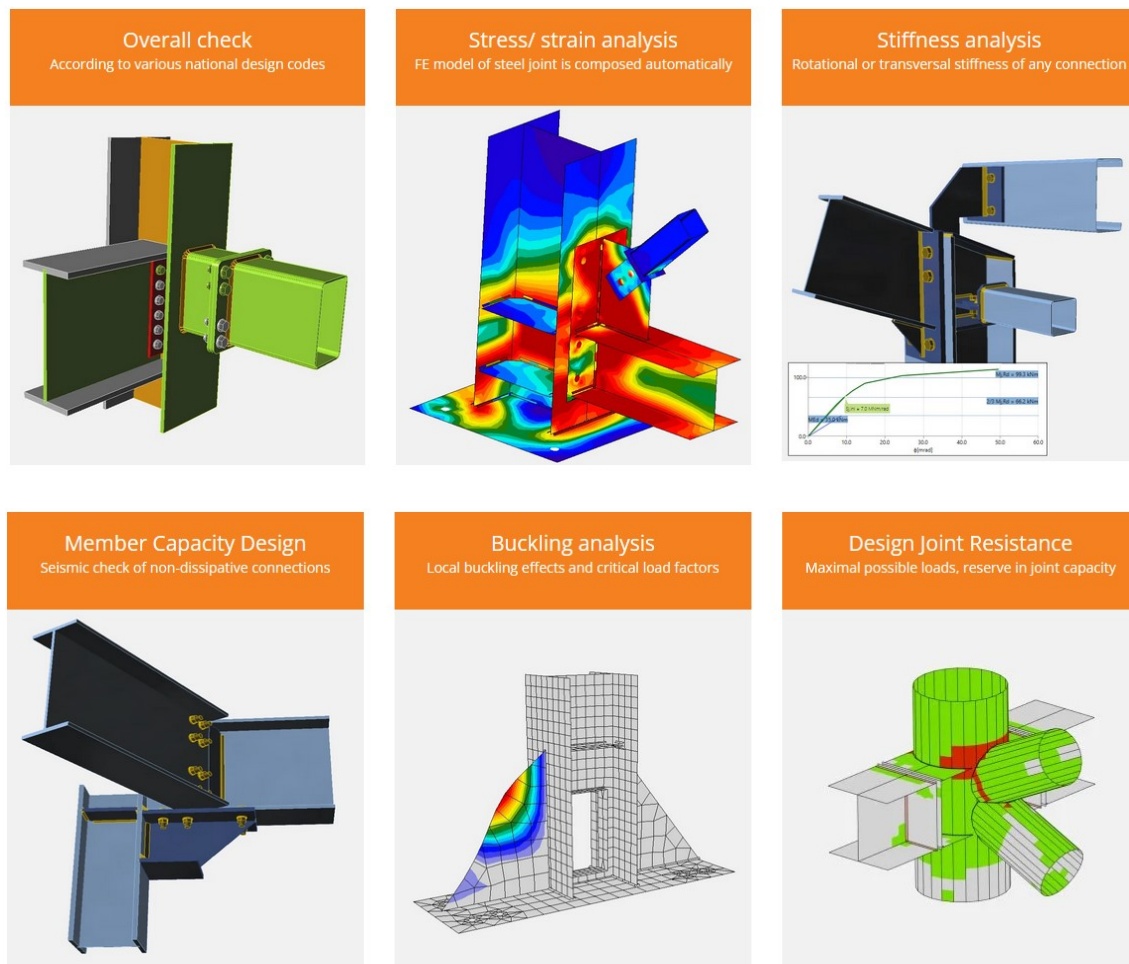


Figure 14 – CBFEM Analysis framework (IdeaStatiCa, 2022)

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4. BIM AIDED STRUCTURAL ANALYSIS

A BIM aided structural analysis (BIMA+) can be seen as the continuation of the methodology Structural Building Information Modelling (S-BIM). S-BIM is the process of analysing and designing a structural solution based on a BIM architectural model, avoiding the creation of a structural model from scratch. A common workflow is for example Revit – ETABS or ArchiCAD - SAP. The S-BIM model is subsequently federated with the other professional models.

The BIMA+ can have as starting point the model created in S-BIM or the model created by traditional means. BIMA+ allows the engineer to perform a more refined analysis with assistance of BIM features. In this case, it is proposed to take advantage of the powerful tool of steel detailing connection that the BIM software has, since it allows to detail connections that cannot be modelled in structural analysis software. Structural analysis software don't allow to detail the steel connection and catch the behaviour from it. In order to consider the stiffness of the connection, a partial fixity value can be assigned to the beam or column. The partial fixity value can be calculated with the Component Method proposed in EN1993 but this method is inaccurate for complex connections. On the opposite, the BIM software allows the user to detail the connection and with the help of another connection software, it is possible to accurately obtain the actual properties of the connections to later assign them to the structural model.

4.1. Traditional analysis design procedure

Conventionally, the analysis starts by assuming that the joints are either pinned or rigid. Joint behaviour is therefore introduced in the structural analysis as a previous morphological assumption in a simple way. This first design decision of the type of connections used allows to fulfil the overall structural analysis without the need of dealing with the joint design till the structural design is complete. The joint design is accomplished as a final step, detailing the joint according to the firstly assumed rotational behaviour: rigid or pinned. The structural design flowchart is shown in Figure 15.

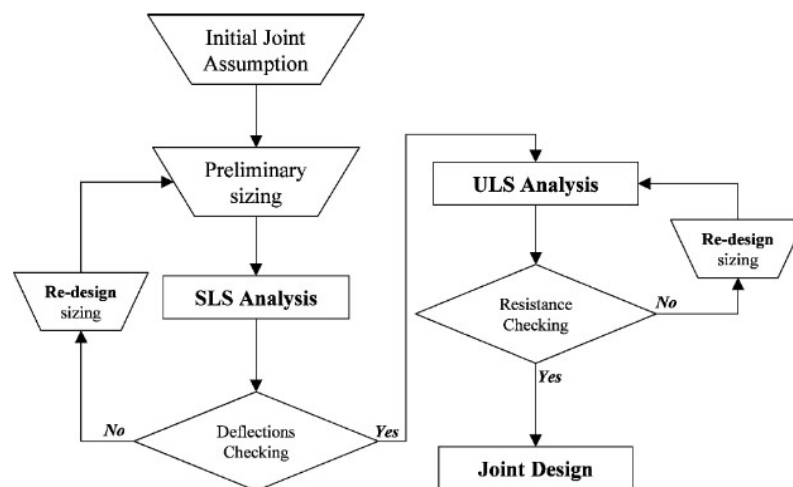


Figure 15 – Traditional structural analysis (Cabrero and Bayo, 2005)

4.2. Proposed analysis design procedure

The previous flowchart becomes more complicated in the case of semi-rigid joints. With the available analysis methods (among them, the component method proposed in EN 1993 should be highlighted) the joint must be completely detailed in order to be able to obtain its stiffness and resistance characteristics. However, to detail the joint, it is necessary to know in advance the size of the attached structural profiles. Conversely, to obtain the structural profile sizing it is necessary to know the joint characteristics in advance. This comes to be a point of no-return: without sizing there is no joint, without joint there is no sizing. The designer must stand out to an increasingly iterative and tedious process as everything influences everything.

A design method suitable for semi-rigid joints is proposed and schematically presented in Figure 16. Apart from minimizing the need for iterative calculations, the main advantage is its similarity to the design method used at present for traditional types of joints (pinned and rigid): the structure is sized according to design assumptions, and the joint is detailed afterwards. As it has been demonstrated in literature, most connections behave as semi rigid, and their behaviour has great influence on the global structural behaviour. Therefore, the starting point is assigning the spring according to the established limit for pin and fixed joints, according to the code. This step of assigning the code limit stiffness values allows to converge to the final solution more quickly.

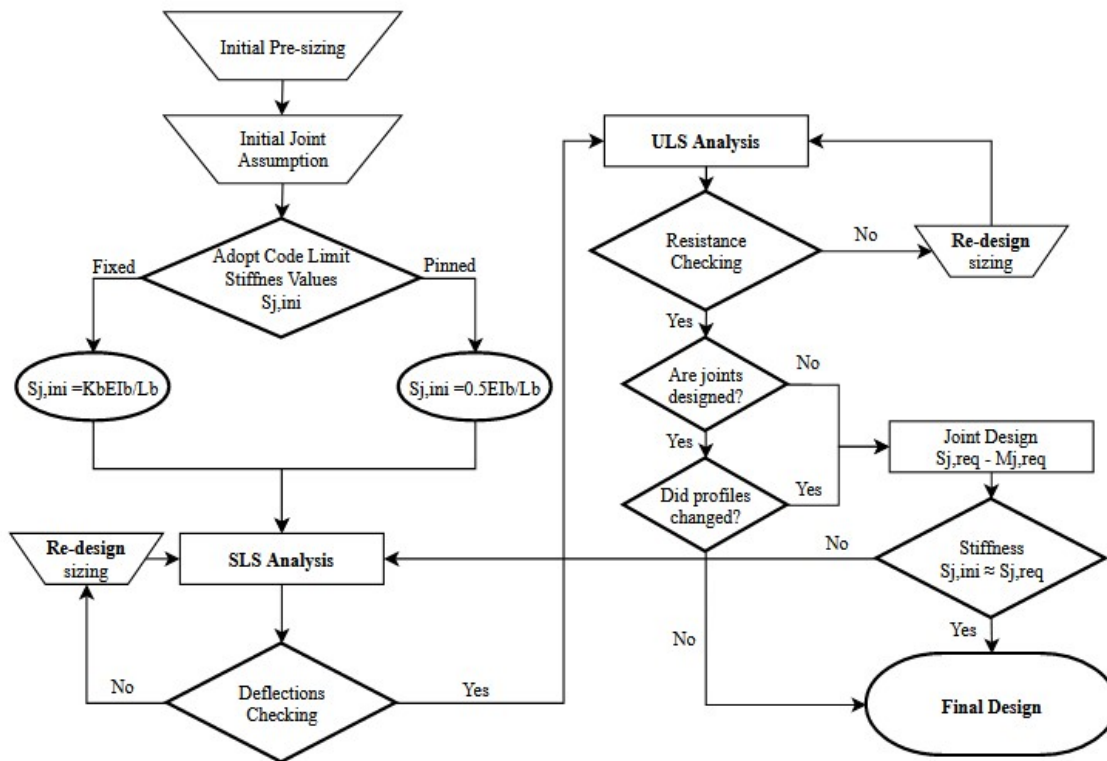


Figure 16 – Proposed design method for semi-rigid elastic analysis

Secondly, it has been observed that for structures in seismic areas, their design is driven by the Service Limit State (SLS) and subsequently by the Ultimate Limit State (ULS) therefore this is the reason for checking SLS before ULS. After the first cycle of SLS and ULS check the model is imported in the BIM software to detail the connections.

Afterwards, the connections are imported to the CBFEM connection software where they are designed with the load combinations from the ULS. Later on, the stiffness analysis of all joints is done and the calculated stiffness are introduced in the structural model and SLS and ULS are checked again. If there is any profile modification, this is updated in the BIM software and synchronized with the CBFEM software. This process of analysing the structures, detailing the connection and designing and performing the stiffness analysis is repeated until the stiffness of the connections converges with the ones introduced formerly in the structural model. This might seem an exhausting work but nowadays the computational power of computers and software make this an easy task.

The interoperability between structural software and BIM software allows to avoid rework in introducing profiles into the BIM software while the interoperability between the BIM software and the steel connection design permit an easy syncing, reducing time spent in the connection design.

Note: It is important to highlight that despite all pinned joints have some stiffness, the stiffness of pinned joints in the weak axis is not taken into account in the design. This stiffness is usually very low and the structural design would get more complex and the influence of this joint is of low relevance. The stability of members shall be faced with engineering judgement providing lateral bracings to avoid undesired premature low resistance.

4.3. Software

For the dissertation the software were selected considering the ones that are most used in Latino America and Europe. This does not mean, by any means, that exactly these software need to be used in order to have a BIM aided structural analysis. Other equivalent software could be an option.

In Latino America, as mentioned in chapter 3, the purchase of software means a high investment for the companies. Thus, software that are able to design both steel and concrete structures have been preferred by structural design offices. Additionally, Latino America has a great influence from U.S.A, which can be seen, for example, in the adoption of AISC as the steel design code. American structural software has been preferred over those from EU or UK. As a result, the structural analysis software ETABS from CSI is usually chosen.

On the other hand, and despite the reasons presented, European software is selected to create the BIM model and to perform the connection design. Tekla Structures has been the leader for steel connections detailing since it introduced numerical control (NC) files that control the motion of computer numerical control (CNC) machine tools. NC files are used during the manufacturing process a machine tool or machining center drills, cuts, punches or shapes the piece of material. These feature has made Tekla Structures popular among steel manufacturers.

IdeaStatiCa software has become the world-leading software for steel connection design due to its versatility, since it allows to design any type of steel connection with any geometry or loading. Despite

no independent survey was found regarding the use of software, Figure 17 shows a graph with the results of the survey conducted by IdeaStatiCa, where they asked their customers to identify what software do they use along with IdeaStatiCa to design steel structures.

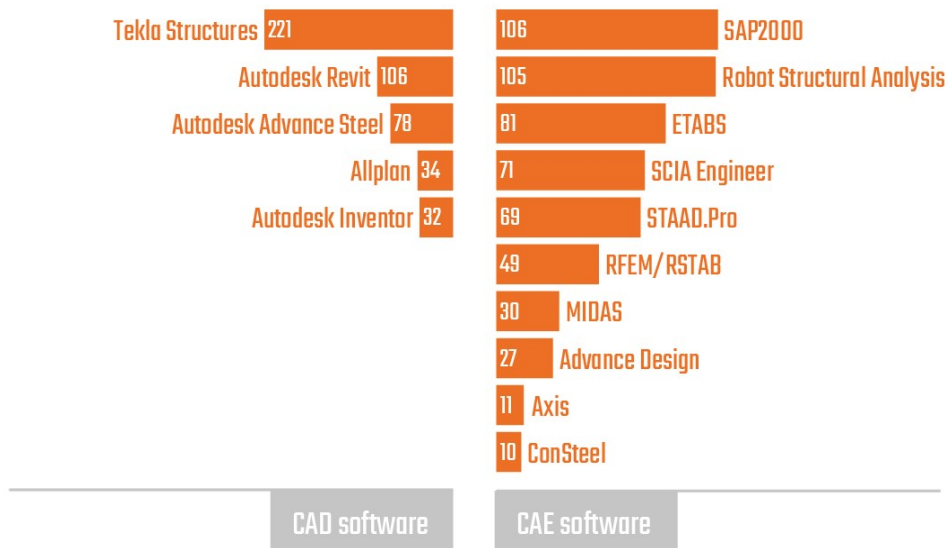


Figure 17 – Most used CAD/CAE software (IdeaStatiCa, 2022)

4.3.1. BIM Software

Tekla Structures, nowadays included in the Trimble portfolio, is a 3D BIM software for modeling building structures. Tekla Structures allows to create, combine, manage and distribute accurate multi-material models full of construction information. It is intended for design, detailing and information management from conceptual planning to fabrication and construction on site. Tekla optimizes the entire process of design, detail and fabrication by allowing the user to visualize the constructible 3D building structure, create all structures with full details and automatic clash checking. Finally, drawings, reports and CNC data can be automatically created from the 3D model (Construsoft, 2022).

4.3.2. Structural analysis software

ETABS is an engineering software product that caters to multi-story building analysis and design. It includes modeling tools and templates, code-based load prescriptions, analysis methods and solution techniques, all coordinate with the grid-like geometry unique to this class of structure. Basic or advanced systems under static or dynamic conditions may be evaluated using ETABS. For a sophisticated assessment of seismic performance, modal and direct-integration time-history analyses may couple with P-Delta and Large Displacement effects. Nonlinear links and concentrated PMM or fiber hinges may capture material nonlinearity under monotonic or hysteretic behavior. Interoperability with a series of design and documentation platforms makes ETABS a coordinated and productive tool for designs which range from simple 2D frames to elaborate modern high-rises (CSIamerica, 2022).

4.3.3. Steel connection design software

IDEA Connection is a software for the analysis & design of steel connections according to EN1993 and AISC codes, that is based on the CBFEM previously presented. As mentioned before, CBFEM offers a detailed analysis of a connection and design “beyond the code”, since it uses FEA to calculate the internal forces within a joint. This enables the engineer to model any connection even if it is not covered by current standards, such as EN1993. At the same time, as mentioned in 4.3.3, it offers some unique features like Local Buckling and Stress/Strain analysis which provides more information for the behavior of the connection and could not be done with other software based on CM formulation.

4.4. Interoperability and syncing

In simple terms, BIM interoperability is when two different systems can work together and exchange information. Interoperability in computing can be seen where one form of software can work and interact with another. When two different devices made by separate manufacturers work have the ability to work together, that is interoperability. With software, users want to switch between different products without having to reenter their data each time. Their data should stay the same and be able to transfer between these different systems. This is important when it comes to BIM.

When it comes to BIM practices and interoperability, ‘exchange’ is a critical word. This is why a common language is needed. Industry Foundation Class (IFC) is the standard here. IFC makes up the base of BIM data exchange methods. It is the standard that various stakeholders use for communication. This is an excellent example of interoperability in action – where multiple departments can use one standard to maintain a clear and consistent flow of information.

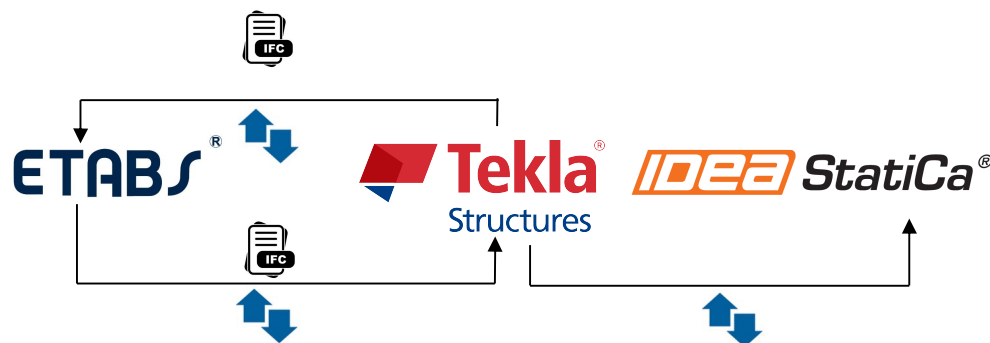


Figure 18 – Intended data exchange schema

Interoperability in this dissertation is based on a structural design oriented project. The different parties involved in structural design like, structural designer, connection detailer and/or technical drafter need to work with software that are interoperable. The interoperability between the software is tested with the use of IFC and Plug-ins, according to the previous schema (see Figure 18). The structural model is exported to the BIM software through IFC and Plug-in subsequently the model with the detailed connections is exported through the BIM link available in the CBFEM software.

4.4.1. Plug-ins

Tekla Structures – CSI Etabs

The extension is designed to exchange structural objects between Tekla Structures and Computer & Structures Inc. ETABS Analysis and Design (A&D) application. The link allows the exchange of data in two directions. It permits to transfer the structural model data from Tekla Structures to ETABS, and to insert the ETABS model into a blank Tekla Structures model.

Either the full model can be transferred or just part of it excluding secondary members that are not required to be included in the member design. It is possible to transfer all the loads modelled in Tekla Structures to ETABS. Also, the normal results update procedure (maximum end reactions and member size revisions in ETABS) and the model merge function are available within this extension.

When importing into a blank Tekla Structures model, native Tekla Structures steel and concrete beams, columns, slabs, shear walls etc. will be created.

Both compatible versions of Tekla Structures and ETABS need to be loaded on to the same machine where the transfer is performed (Wharehouse.Tekla, 2022).



Figure 19 – Plug-in Tekla Structures – CSI Etabs (Tekla Structures, 2022)

BIM Link Tekla Structures – Idea Connection

IDEA Connection can be linked through a macro that creates a button within TEKLA, that allows to export a connection with all the relevant parts. If Tekla is already installed, this is automatically done when installing Idea Connection. The workflow is very simple: The project is opened in Tekla Structures, and then the “IDEA Connection” icon is clicked to select a node and all of its parts. An automatic data transfer is started that transforms a connection modeled in Tekla Structures into an IDEA Connection project, which will help to analyze and design the connection.



Figure 20 – Plug-in Tekla Structures – Idea Connection (IdeaStatiCa, 2022)

Synchronization

As seen in the proposed flowchart (see ¡Error! No se encuentra el origen de la referencia.), the design process is an iterative way how to mechanically arrange the structure parts in a way that it will work and pass the code-check. Usually, it takes a few changes in the whole process. The Synchronization function for the current item is useful in these cases. With this function, it can easily

update an existing design of the IDEA StatiCa Connection project exported from the Tekla Structures can be easily updated. The originally defined Load effects are saved. This function is crucial to the link between the IDEA StatiCa project file and the Tekla Structures source file. The directory of the IDEA StatiCa project file or its name cannot be changed and the Save function shall be used.

IDEA Connection does not support IFC but has a link for all the software shown in Figure 17.

4.4.2. IFC

The main property of Open BIM technology and its main advantage is that it is based on open and public standard interchange formats called Industry Foundation Classes better known as IFC, so that the contents of the BIM project are not linked to any specific application or program.

IFC is a global standard used to describe, share and exchange construction and facilities management information. As a data format IFC is neutral (not the product of or favoring any particular vendor) and non-proprietary. Using IFC means that construction professionals can use the software application(s) of their choosing to work with data. IFC is supported by about 150 software applications worldwide and this kind of interoperability is crucial as AEC becomes increasingly collaborative (NBS, 2017).

IFC models can be inserted as reference models to Tekla Structures, and optionally convert the inserted IFC objects into native Tekla Structures objects by using the direct conversion, or selected IFC reference objects using conversion change management. Inserted IFC reference models can be used for clash checking, reporting and scheduling.

Characteristics of supported IFC schemas

Tekla Structures supports the IFC 2x3 (recommended) and IFC 4 schemas. The IFC insert IFC2X3 functionality has the IFC certification granted by BuildingSMART international (SupportTekla, 2021). The IFC certificate confirms that the software is able to import IFC with sufficient quality, though it cannot guarantee that the IFC utilities provided by the software is bug-free (Ifcwiki, 2008).

Supported entities

The IFC reference model insert in Tekla Structures supports all the sub-objects of the IfcBuildingElement class and sub-objects of the IfcProduct class including:

- Architectural entities
- Structural entities
- Building services entities

Supported formats

The range of IFC formats supported by Tekla Structures 2022 is the following:

- IFC (.ifc) and ifcXML (.ifcXML) formats are supported.
- You can use compressed (.ifcZIP) or uncompressed insert files.
- IFC4 does not support ifcXML.

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5. CASE STUDY – INDUSTRIAL STEEL BUILDING

An industrial building is proposed as case study for the particular interest of the parties involved in the dissertation. The author has professional experience in the design of steel buildings and industrial buildings is 80% of the manufactured projects of the sponsor company. The case study was initially designed with the traditional approach. The proposed methodology is subsequently used and the results obtained in the two approaches are compared. The industrial building is part of the extension project of the plant for the holding group Veconsa located in Guayaquil, Ecuador. The warehouse will stock raw material for food processing and is to be designed to withstand the normative seismic forces, as well as static forces.



Figure 21 – Case study industrial steel building

5.1. Description

The industrial building has a typical gable roof with an implantation of 31,05 m \times 35,35 m. The column height is 6 m while the highest roof point is at 10,49 m. The spacing between frames is 6m, except the last module that is 5,35 m, as shown in Figure 22. The building is asymmetrical in X axis since the roof top is located at a distance of 15,05 m, 0,475 m away from the midspan (see Figure 23).

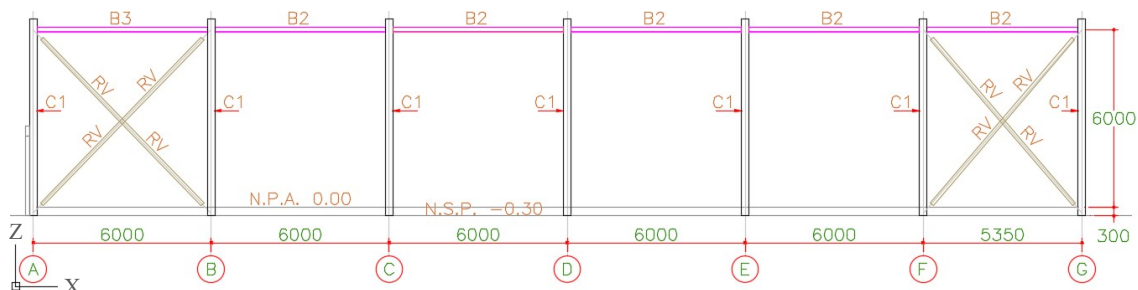


Figure 22 – Elevation with x concentric braces

Two different types of structural solutions are used to withstand the normative forces. In the X direction, the lateral resistant system is Special Moment Frames (SMF) while in the Y direction is X concentric steel braces. The live load is 60 kg/m² and the super imposed dead load is 25 kg/m². The

peak ground acceleration (PGA) 0.30 m/s^2 while the maximum spectral acceleration is 0.72 m/s^2 . See appendix 4 for a more detailed analysis of the spectral forces. The behavior factor q is 5 for the X direction and 4 for the Y direction. See appendix 3 for the response spectrum formulation.

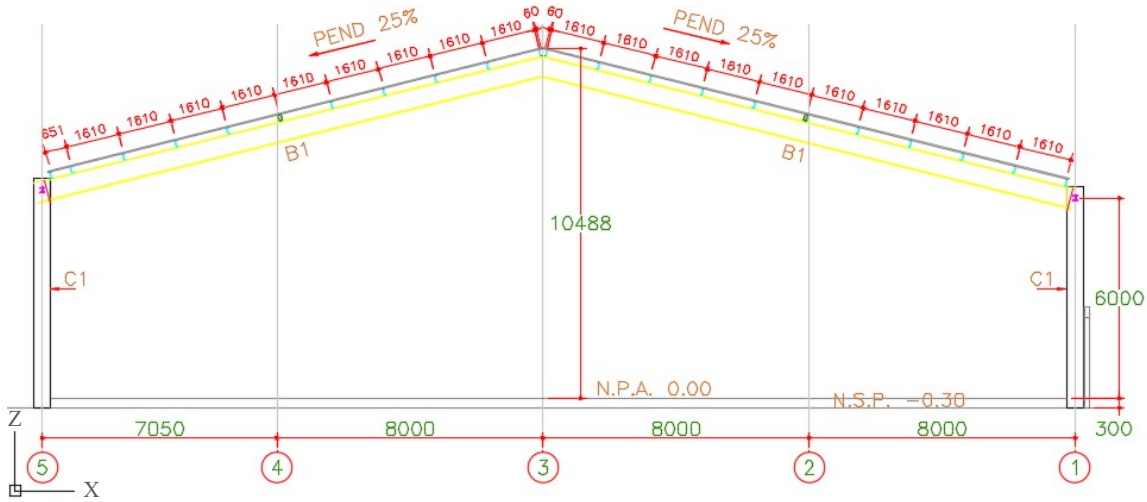


Figure 23 – Elevation with SMF

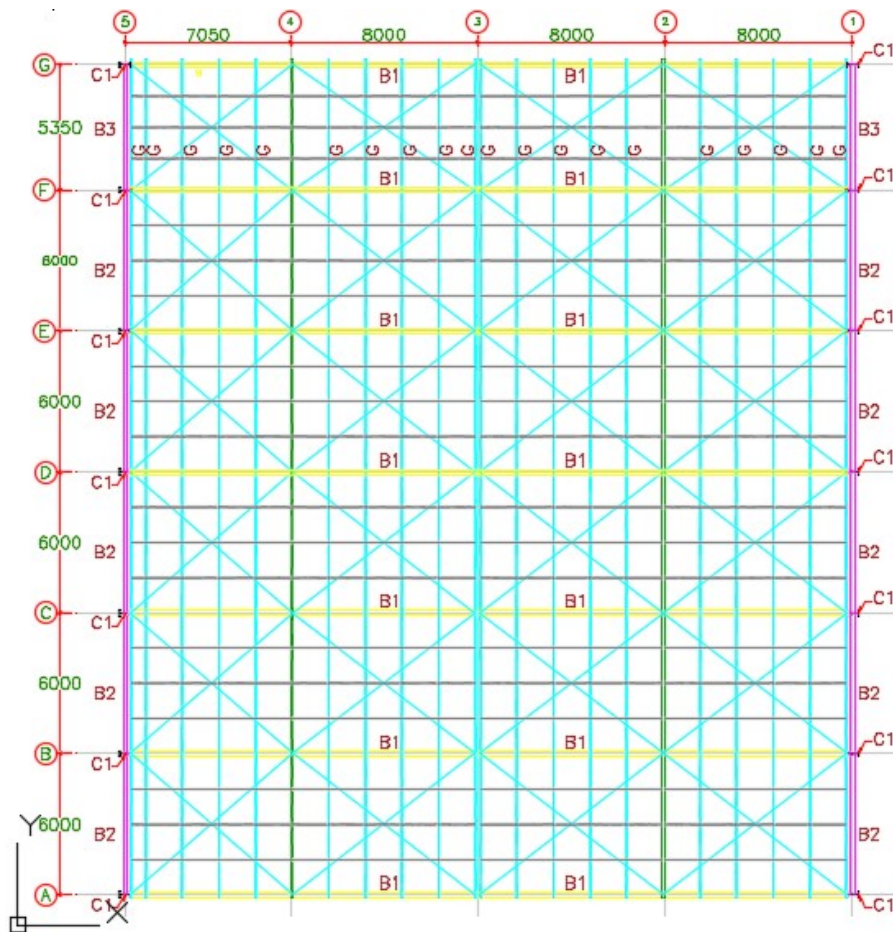


Figure 24 – Structural plan

5.2. Traditional design approach

As mentioned in Chapter 4, the traditional design approach is to assume idealized connections, which can be either fixed or pinned. In this case, the design of all steel members was performed by checking Serviceability Limit States (SLS) and Ultimate Limit States (ULS) (see Figure 28) and, finally, the design was completed with CBFEM software to get the final connections. In Ecuador, typical industrial buildings are designed with fixed supports (see Figure 25), in contrast to Europe where all supports are pinned and stability of the building is achieved by strong column-beam joints.

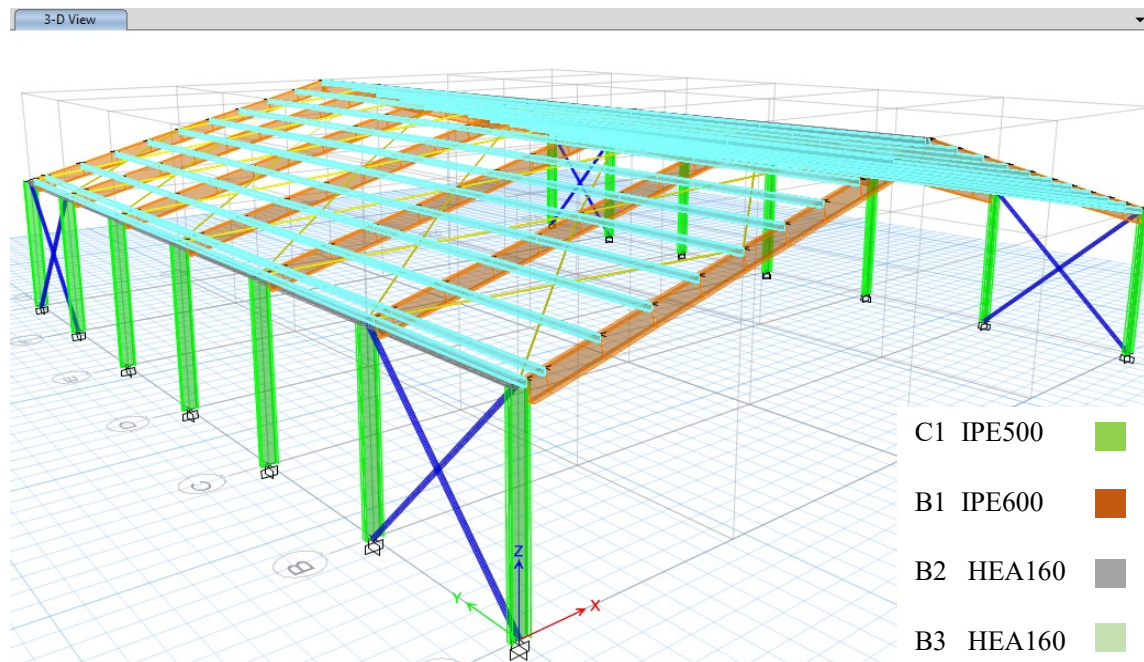


Figure 25 – Structural analysis model

The first two modes of vibration were translational (see Figure 26) with a period of vibration of 0.319s in X axis and 0.312 in Y axis. The third mode of vibration was rotational with a period of vibration of 0.219s.

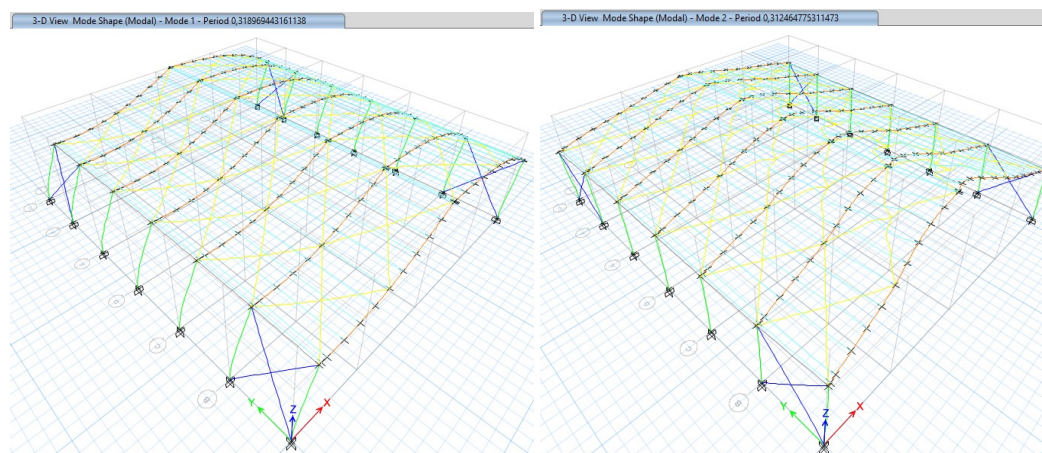


Figure 26 – Modes of vibration of traditional design structure

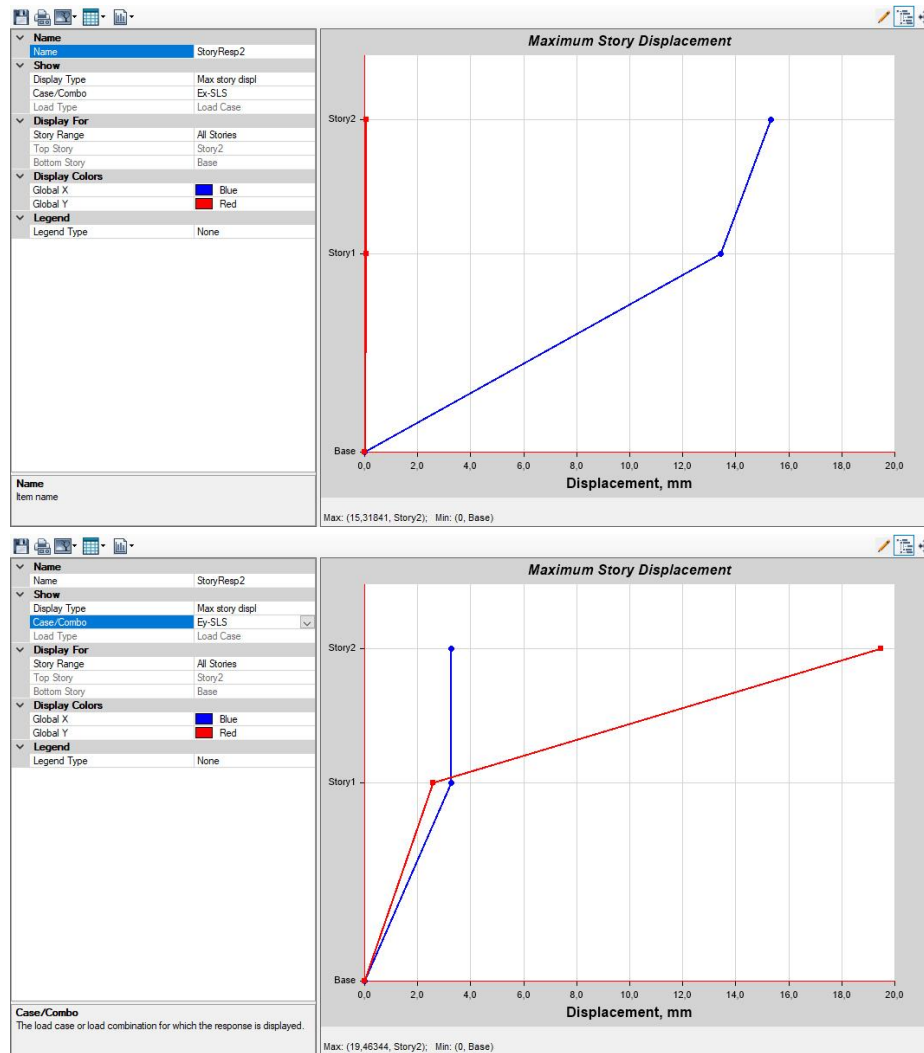


Figure 27 – SLS check of traditional design structure

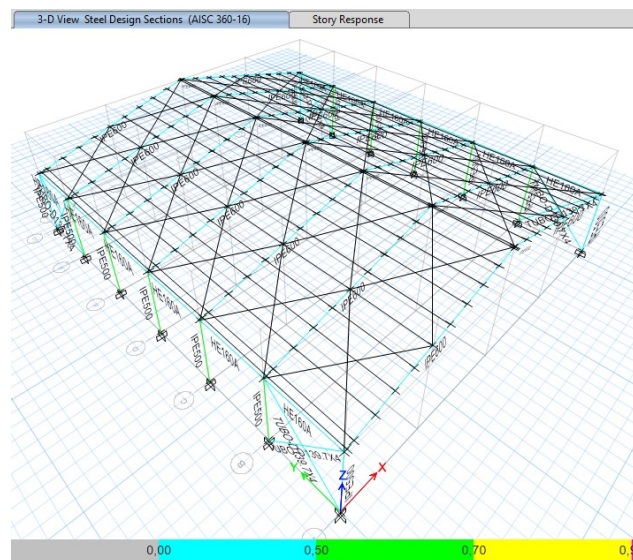


Figure 28 – ULS check of traditional design structure

5.3. Applied BIM methodology

Like in any other structural analysis approach, a pre-sizing is needed without performing any structural analysis. This is why the designer's experience is an important factor at this stage because based on an accurate choice of steel profiles less cycles will be needed to reach the final design. Despite it may lead to an underestimation since serviceability tend to be the critical factor, the beams can be sized according to the maximum expected bending moment.

The design was performed according to the proposed methodology BIMA+. The same assumption of idealized connections (either fixed or pinned) is considered, but the stiffness value to initiate the analysis are defined according the code limits. The model remains exactly as shown in Figure 25 but the limit stiffness of the connections is introduced, according to the values set in Table 1. As mentioned earlier, the stiffness in the weak axis of fixed and pinned joints is not taken into account.

Once the SLS and ULS checks are performed the structural model is exported to the BIM software.

Table 1 – Initial joint stiffness to initialize structural analysis

| Member | Profile | Steel type | Modulus of Elasticity MPa | Inertia cm ⁴ | Length cm | Assumed joint | Code Limit Stiffness | $S_{j,ini}$ kN-m/rad |
|--------|---------|------------|---------------------------|-------------------------|-----------|---------------|----------------------|----------------------|
| Column | IPE500 | A572 Gr.50 | 210000 | 48200 | 600 | Fixed | 25EI/L | 401577 |
| Beam | IPE600 | A572 Gr.50 | 210000 | 92080 | 3209 | Fixed | 25EI/L | 143439 |
| Beam | HEA160 | A572 Gr.50 | 210000 | 1673 | 535 | Pinned | 0,5EI/L | 313 |
| Beam | HEA160 | A572 Gr.52 | 210000 | 1673 | 600 | Pinned | 0,5EI/L | 279 |

5.3.1. Importing through plug-in and IFC to BIM software

This process is done through IFC file (see Appendix 1) and the plug-in (see Appendix 2) downloaded from warehouse Tekla website.

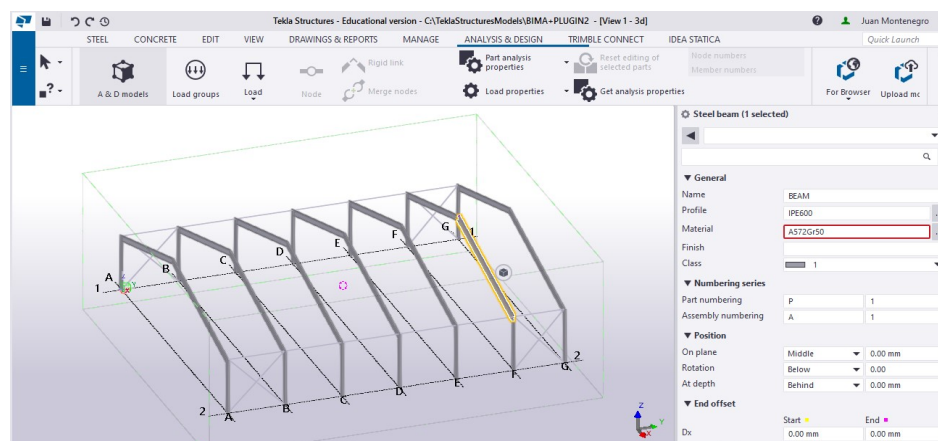


Figure 29 – Imported model created from structural model

It can be seen in Figure 29 that the purlins and horizontal steel braces are missing. When importing either using IFC or Plug-in, Tekla Structures did not recognize non-standardized sections like cold

formed profiles used as purlins and steel rods used as horizontal bracing. Errors like in the following picture appeared for each non-standardized element (see Figure 30).

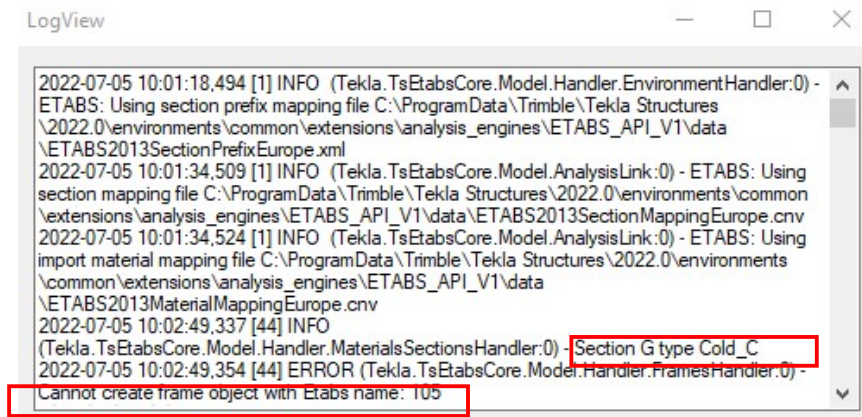


Figure 30 – Typical error for non-standardized profiles when importing to Tekla.

5.3.2. Steel connection detailing and exporting

Bolted connections are detailed for all different type of connections using Tekla Structures. These connections are transferred to IdeaStatiCa using the BIM link (see Figure 31). It was found that the loads were not imported in the BIM software, therefore they were exported with excel sheets from the structural software.

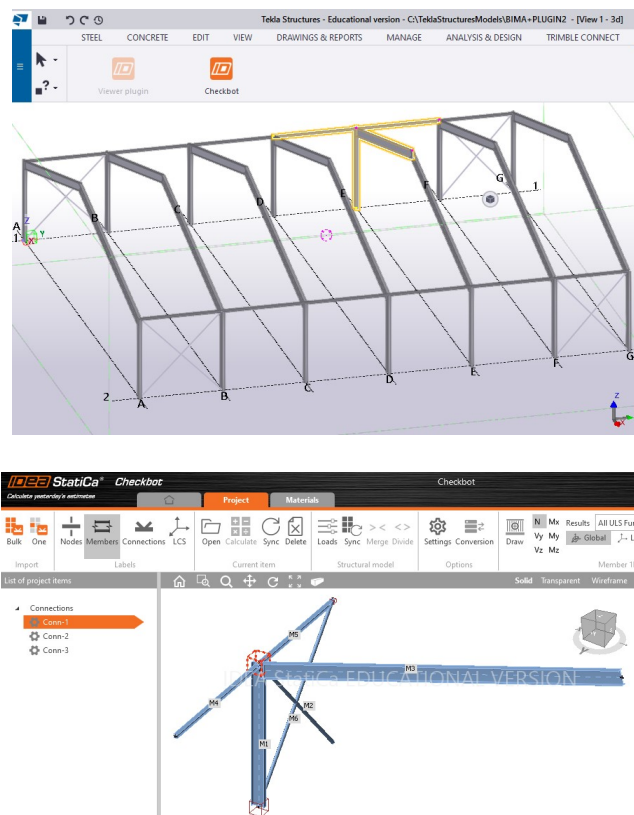


Figure 31 – Exporting connections to CBFEM software

5.3.3. Steel connection design process

The connection analysis is performed for each type of connection and the stiffness is obtained with the CBFEM software (see Figure 32).

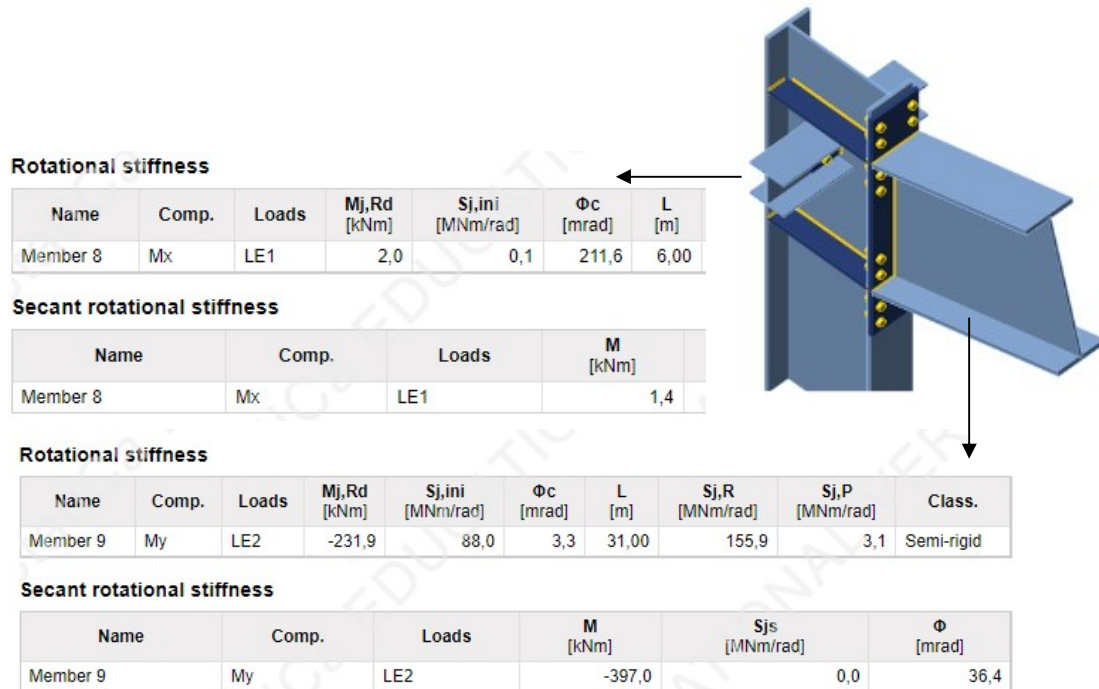


Figure 32 – Stiffness analysis result for pinned and fixed joints with BIMA+ approach

5.3.4. Assigning stiffness to models and exporting

The calculated stiffness are subsequently assigned in the 3D BIM structural model. For example the stiffness of the simple joint of 0.1MNm/rad (100kNm/rad) is assigned as shown in Figure 35. The model is subsequently exported through IFC and plug-in.

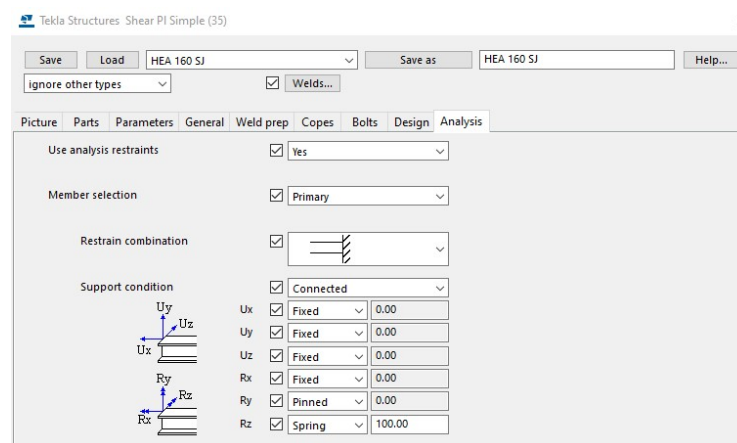


Figure 33 – Assignment of partial fixity restraints to BIM model.

It was found that the assigned manufacturing operations required to detail the connection created many analytical joints difficulting the structural analysis (see Figure 34). This repetitive issue required time to solve therefore the approach of assigning the stiffness directly to the model in the structural analysis software is more recommended. It is recommended to populate the BIM model with these data once the final design is achieved since it will enable further analysis and may be useful for retrofitting.

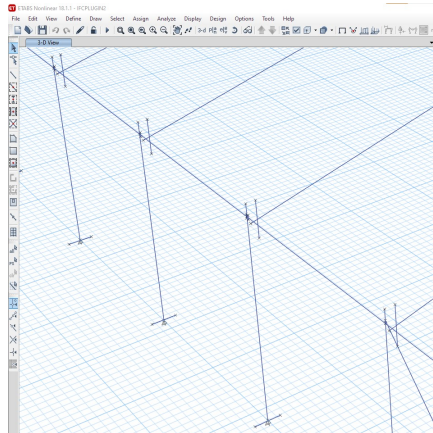


Figure 34 – Structural model with joints issues.

The calculated stiffness are subsequently assigned in the structural model. For example the stiffness of the simple joint of 0.1MNm/rad (100kNm/rad) is assigned as shown in Figure 35. The structural model is run again to check SLS and ULS. In case there is any change of profile, this is updated in the BIM software and synced with the CBFEM connection software to redesign the connection and obtain the updated stiffness. This process is repeated until no change of profile is needed.

Frame Assignment - Releases/Partial Fixity

| Frame Releases | Release | | Frame Partial Fixity Springs | | |
|--------------------------------------|-------------------------------------|-------------------------------------|------------------------------|-----|----------|
| | Start | End | Start | End | |
| Axial Load | <input type="checkbox"/> | <input type="checkbox"/> | | | kN/m |
| Shear Force 2 (Major) | <input type="checkbox"/> | <input type="checkbox"/> | | | kN/m |
| Shear Force 3 (Minor) | <input type="checkbox"/> | <input type="checkbox"/> | | | kN/m |
| Torsion | <input type="checkbox"/> | <input type="checkbox"/> | | | kN-m/rad |
| Moment 22 (Minor) | <input type="checkbox"/> | <input type="checkbox"/> | | | kN-m/rad |
| Moment 33 (Major) | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | 100 | 100 | kN-m/rad |
| <input type="checkbox"/> No Releases | | | | | |

Figure 35 – Assignment of partial fixity restraints to structural model.

5.4. Results

The joints stiffness influences greatly the global behaviour by modifying the internal forces of structural members. When the steel profiles don't need to be changed, it can be concluded that the structural analysis has reached the convergence point, meaning that the structural design is finished. Finally, results regarding structural integrity are obtained.

5.4.1. Modes of vibration

The modes of vibration of the structural models designed with different approaches can be seen in Table 2. By adding the stiffness to the simple joints in the analysis it is shown that the simple joints are adding some stiffness although this increase is only 2,8%. On the other hand, the influence of semi-rigid joints is greater, and it represents a decrease of 6,8% on the period value.

Table 2 – Modes of vibration of structural models

| | Type of mode | Design approach | | |
|---------------|-----------------|----------------------|--------|-----------|
| | | Traditional | BIMA+ | Deviation |
| | | Periods of vibration | | |
| Mode 1 | Translational X | 0,319s | 0,328s | +2,8% |
| Mode 2 | Translational Y | 0,312s | 0,297s | -4,8% |
| Mode 3 | Rotational Z | 0,219s | 0,222s | 1,3% |

5.4.2. Seismic forces

The seismic forces remain unaltered, as presented in Table 3, since the modes of vibration are already in the peak of the acceleration response spectrum and additionally the seismic weight is the same since in this case no change of profiles has been done.

Table 3 – Shear base reactions of structural models

| Output Case | Case Type | Step Type | Design approach | | | |
|-------------|-------------|-----------|-----------------|-----------|-------------|-----------|
| | | | Traditional | BIMA+ | Traditional | BIMA+ |
| | | | FX [tonf] | FY [tonf] | FX [tonf] | FY [tonf] |
| Ex | LinRespSpec | Max | 9,91 | 0,01 | 9,91 | 0,01 |
| Ey | LinRespSpec | Max | 0,01 | 9,34 | 0,01 | 9,34 |

5.4.3. Drifts

The drifts are related to the mode of vibration of the structure. Since the period of vibration with BIMA+ in X direction is slightly higher the drift is as well slightly higher 5,5%. In parallel, when with BIMA+ the period of vibration is lower, the drift is lower (see Table 4).

Table 4 – Drifts

| Load case | Type of mode | Design approach | | |
|-----------|---------------|-----------------|-------|-----------|
| | | Traditional | BIMA+ | Deviation |
| | | [cm] | [cm] | |
| Ex | Seismic force | 15,26 | 16,10 | +5,5% |
| Ey | Seismic force | 2,78 | 2,74 | -1,4% |

5.4.4. Joint design

Pinned joints

The obtained pinned joints did not suffer any changes between the two approaches. The stiffness of the pinned connection was accounted in the strong axis. The stiffness of the connection in the weak axis was not accounted since it is negligible and the effort to take into account does not bring any significant benefit to the design. The obtained detailing of the pin connection can be seen in Figure 36.

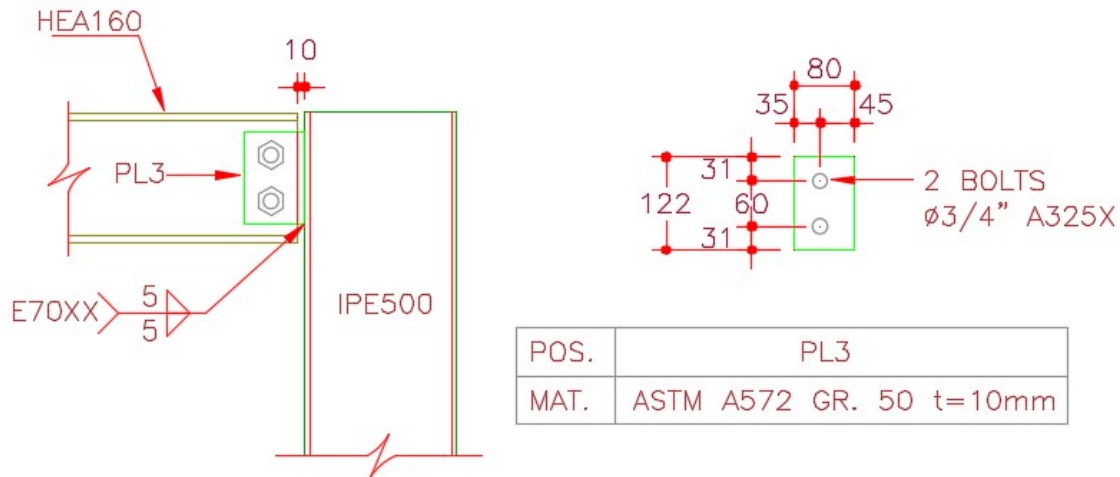
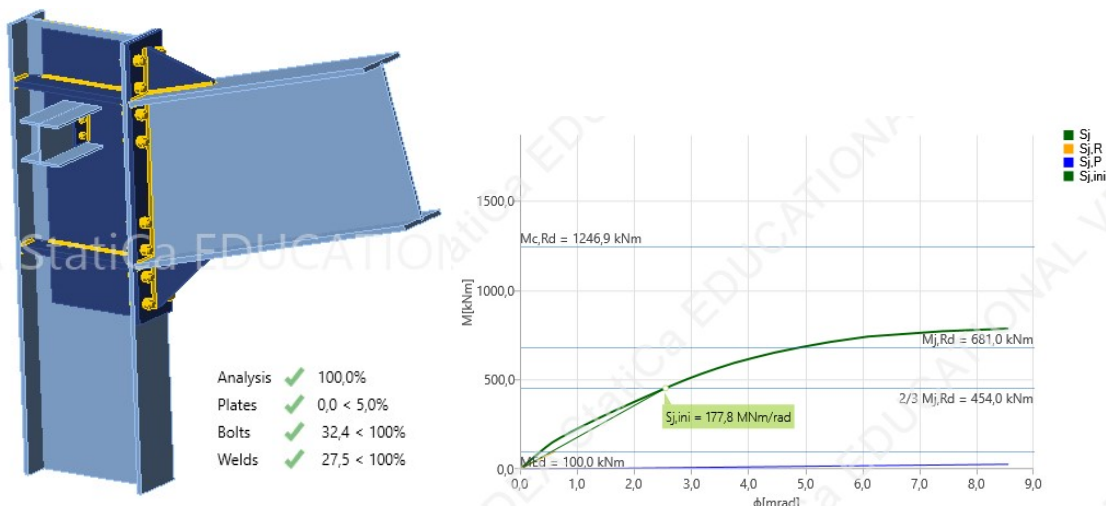


Figure 36 – Pinned connection for beam with traditional and proposed design approach

Fixed joints

The design of fixed connections differs significantly between the two design approaches. It is difficult to achieve an idealized fixed connection and that option requires many strengthening plates like flange and web stiffeners and also, it requires double plate stiffeners on the column (see Figure 37). In conclusion, there was no saving in the profile selection, but there was a reduced use of steel parts in the connection assemblies (see Figure 38 and Figure 39).

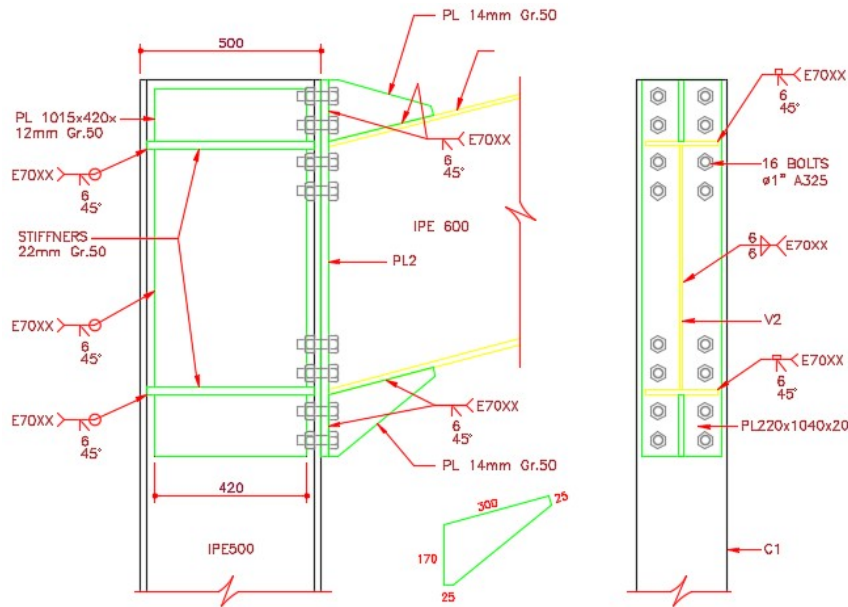
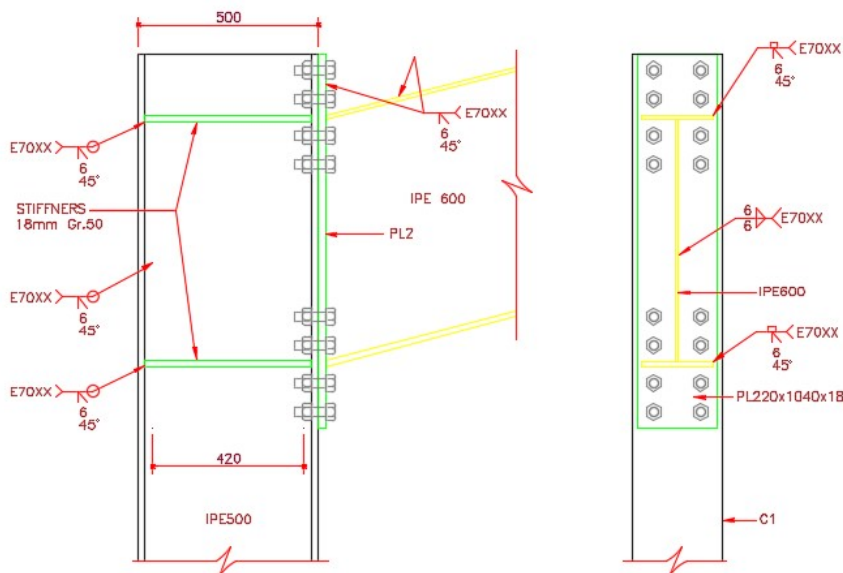


Rotational stiffness

| Name | Comp. | Loads | Mj,Rd [kNm] | Sj,ini [MNm/rad] | Φ_c [mrad] | L [m] | Sj,R [MNm/rad] | Sj,P [MNm/rad] | Class. |
|-----------|-------|-------|----------------|---------------------|--------------------|----------|-------------------|-------------------|--------|
| Member 11 | My | LE2 | 681,0 | 177,8 | 4,9 | 30,00 | 161,1 | 3,2 | Rigid |

Secant rotational stiffness

| Name | Comp. | Loads | M [kNm] | Sjs [MNm/rad] | Φ [mrad] |
|-----------|-------|-------|------------|------------------|------------------|
| Member 11 | My | LE2 | 100,0 | 273,8 | 0,4 |

Figure 37 – Stiffness analysis of fixed connection for column-beam joint with traditional design**Figure 38 – Fixed connection for column-beam joint with traditional design approach****Figure 39 – Fixed connection for column-beam joint with proposed design approach**

Cost of connection

Based on the cost estimation processor of IdeaStatiCa there was a reduction of 37% on the connection.

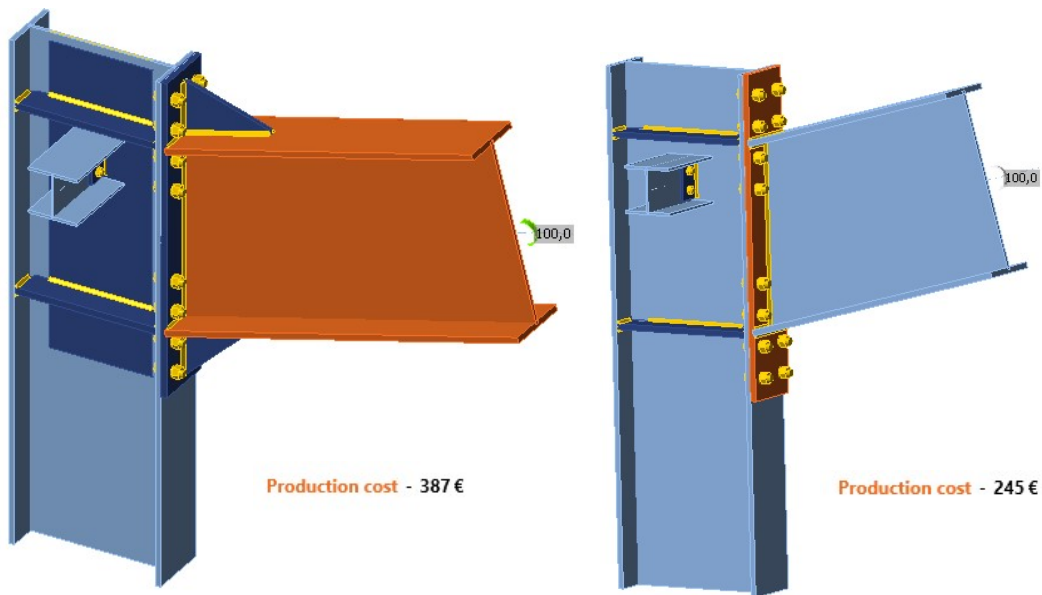


Figure 40 – Cost comparison of connection between different design approaches.

6. CONCLUSIONS

This dissertation has the objective of delivering a practical upgrading of work processes in a structural design office by implementing BIM. A literature review of BIM in structural design was conducted in order to promote the implementation of BIM in structural design offices, well framed in the particular context of Latino American design offices where there is still some aversion against its usage. In this study, the advantages and benefits of the methodology for structural design offices were clearly identified, as well as the challenges. Most of the challenges will be overcome with time, like lack of education and skilled professionals. BIM is of high interest in EU where the European Education and Culture Executive Agency is investing in master programs like BIMA+ which is an exclusive master focused in BIM in the AEC industry.

The literature review about semi rigid steel connections puts in evidence an existing design problem when either fixed or pinned connections are idealized, because in reality, most steel connections have a semi rigid behavior. The behavior of semi rigid connections has been considered since 2005 with the introduction of EN 1993-1-8 and the component method, which is used to calculate the strength and the stiffness of the connection. Nevertheless, its use involves many calculations and is limited to a certain type of joints. These challenges are overcome with the use of CBFEM that enables the design of complex connections. The methodology proposed was developed in the context of BIM aided structural analysis and is based on considering the stiffness of the connections in the global analysis of the building and making use of state of the art software like Tekla Structures and IdeaStatiCa to achieve a higher level of structural design in terms of accuracy and openness of collaboration.

The proposed workflow of BIMA+ is independent and is not influenced by other professional parties involved in the project, therefore structural design offices might take advantage of this approach. As opposed to S-BIM, where a structural model is the result of analyzing and designing a model originated from the BIM architectural model, the BIMA+ approach allows to obtain a BIM structural model without the BIM architectural model. It allows design offices to be ready for the BIM revolution.

The workflow is rational and integrates tasks that a design office might already be doing independently. It facilitates the coordination and collaboration at design and drawings production stage and the creation of a BIM model suitable to be exported to other parties of the project.

The case study was analysed applying openBIM software in an integrated workflow that is here proposed, together with other analysis tools. The case study of an industrial steel building helped to assess the adequacy of the methodology and the interoperability of software involved in the workflow. The observations based on the case study results are followed below.

- While importing the structural model to the BIM software many problems were found. BIM software did not recognize non-standardized profiles nor non-prismatic profiles. This is a problem since, as shown in Figure 6, many columns in industrial steel buildings are built-up and they are normally tapered, with a small section at the base and bigger section at the column-beam joint.

- This situation repeats itself for beams, because these normally have a smaller section at quarter-span and a bigger section at column-beam joints and midspan. Additionally, the analysis results were not imported, thus the joint reactions needed to be exported independently by using .xlsx files directly to the CBFEM software. These issues were found either by using plug-in or IFC. It was found that the process is better with IFC since it requires less computational effort. Using the plug-in to transfer data from structural software to BIM software required a valid installation of both software in the same computer and, additionally, the plug-in initiates the structural software to map the model meaning that great computational effort was needed. The importation through IFC took less time than with the plug-in for the reasons previously mentioned.
- Exporting BIM model to structural analysis software was possible through IFC and plug-in but its use is not recommended since it doesn't add any advantage to the design process. Loads are lost in this process and the targeted benefit of obtaining the stiffness of connections is not possible through this process
- The synchronization function between the BIM and CBFEM software worked extraordinarily. The designed connections were modified according to the changes performed in the BIM software when using the syncing option. In this case, the disadvantage encountered in the BIM software is again the computational effort. In order to export and synchronize the BIM model to the CBFEM software both need to be running. This process takes less time than it would take with the use of the CSI-Tekla plug-in. On the other hand, an advantage is that it allows to select and export a specific joint reducing this way the amount of time on computer processing.
- The obtained interoperability can be visualized in Figure 41:

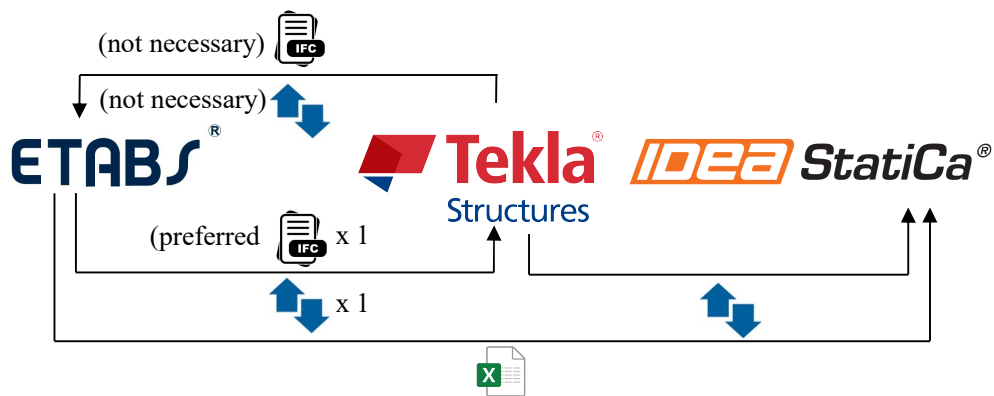


Figure 41 – Obtained data exchange schema

- In order to add the calculated joint stiffness to the structural analysis model, the assignment was needed to be done manually one by one. Although, this did not represent a time investment since most connections were repeated and so it is for most industrial buildings, this might represent a problem for irregular buildings where many types of profiles are designed.
- The use of calculated stiffness for pin joints for example the joint of the beam to the column of the concentric bracings system did not represent any benefit to the design. The reason derives from the structural analysis; the stiffness of the system is achieved by the bracings. The bracing system is

much more rigid than the bending stiffness of simple joints therefore their influence is marginal. The modes of vibration, shear base and drifts were very similar between traditional design and the BIMA+. It can be concluded BIMA+ helps to design simple joints but their influence can be neglected in presence of a much stiffer system.

- On the contrary, the implementation of semi-rigid connections instead of idealized fixed joints resulted in a cheaper design. The semi-rigid connections were less expensive due to the absence of stiffeners. The semi-rigid behavior of connections flexibilized the structure in the frame directions causing the period of vibration to increase, thus the drift was higher, nevertheless it was still within an acceptable range.

Even though the dissertation, comprising its conceptual and practical work accomplished its goals, some issues are still not contemplated due to the time limitation and some improvements that would enhance the work are identified.

- The CSI-Tekla plug-in requires to run both software simultaneously, which requires a high computational effort. The plug-in needs to be improved in order to avoid this process. Moreover, the plug-in should be able to import loads and custom profiles.
- Although, IFC allows the exchange of data with less computational effort, upgrades need to be implemented in order to enable the importation of loads and custom profiles.
- As mentioned before, the stiffnesses of calculated connections were assigned manually to the structural model. This is a repetitive task that could be done by a macro enhancing the workflow.
- After the first importation of the structural model to the BIM model, the design updates were performed manually because another importation would have deleted the connections detailing. A synchronization tool is needed in order to save time.

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LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|-------|---|
| EN | Eurocode |
| AISC | American Institute for Steel Construction |
| IFC | Industry Foundation Classes |
| AEC | Architecture Engineering and Construction |
| PAS | Publicly Available Specification |
| CAD | Computer Aided Design |
| ISO | International Standardization Organization |
| ROI | Return of Investment |
| LEED | Leadership in Energy and Environmental Design |
| IDB | Inter-American Development Bank |
| ECSSO | European Construction Sector Observatory |
| DCL | Ductility Class Low |
| DCM | Ductility Class Medium |
| DCH | Ductility Class High |
| FR | Fully Rigid |
| PR | Partially Restrained |
| CBFEM | Component Based Finite Element Method |
| CM | Component Method |
| FEA | Finite Element Analysis |
| FEM | Finite Element Method |
| S-BIM | Structural Building Information Modelling |
| SLS | Service Limit State |
| ULS | Ultimate Limit State |
| CAE | Computer-Aided Engineering |
| NBS | National Building Specification |

APPENDICES

APPENDIX 1: IMPORT-EXPORT THROUGH PLUG-IN

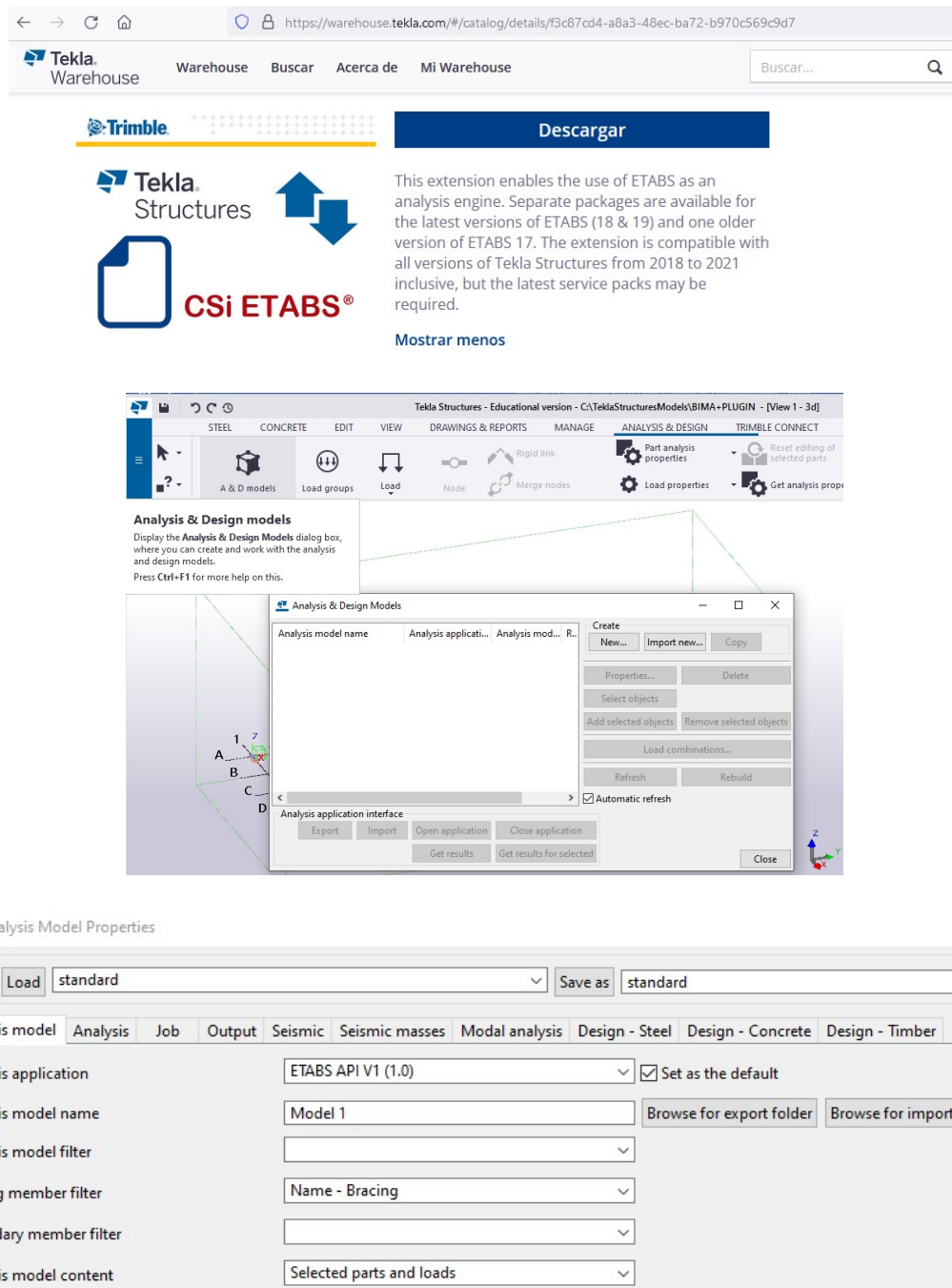


Figure 42 – Import-export through plug-in

APPENDIX 2: IMPORT-EXPORT THROUGH IFC

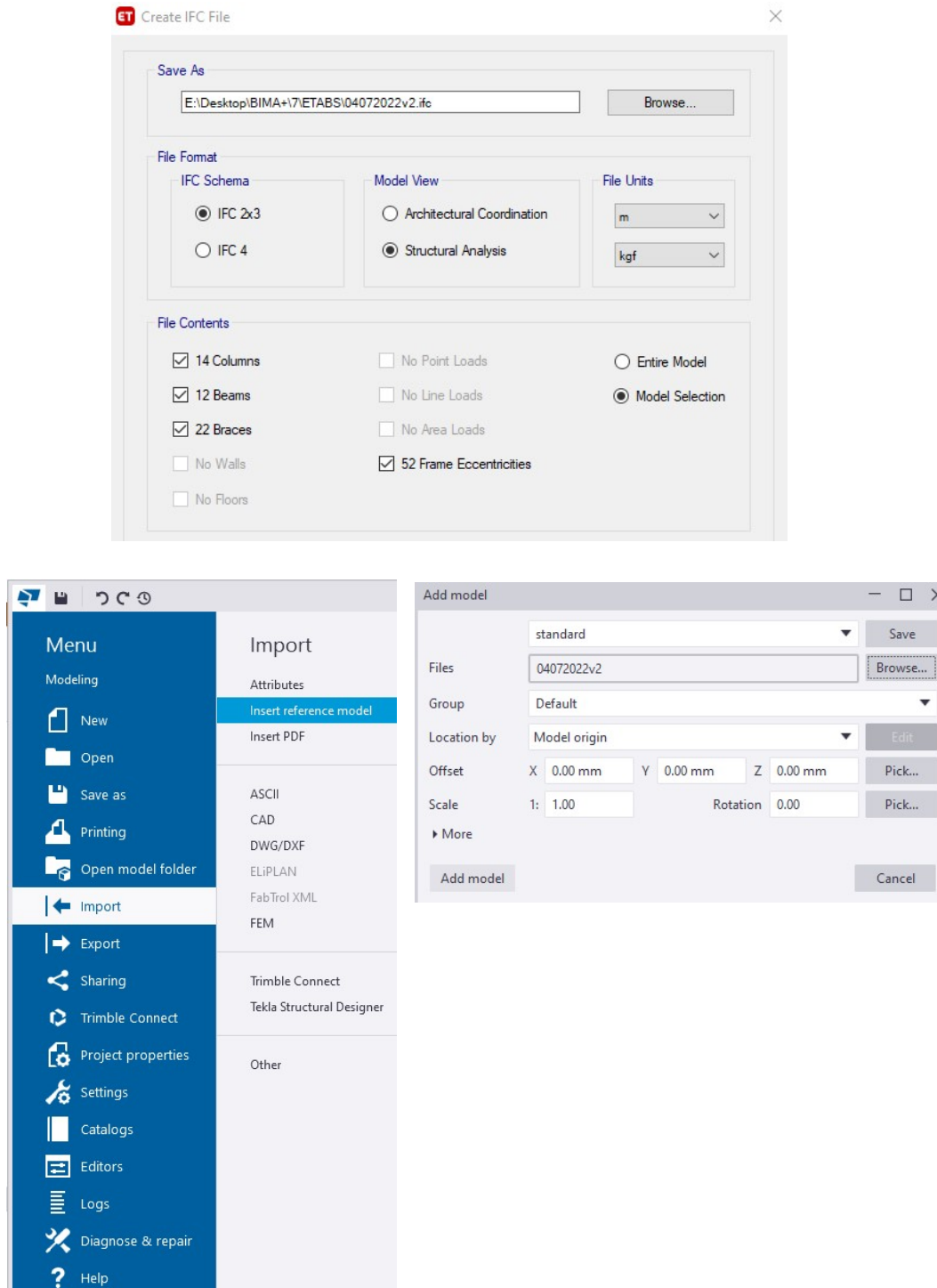


Figure 43 – Import-export through IFC

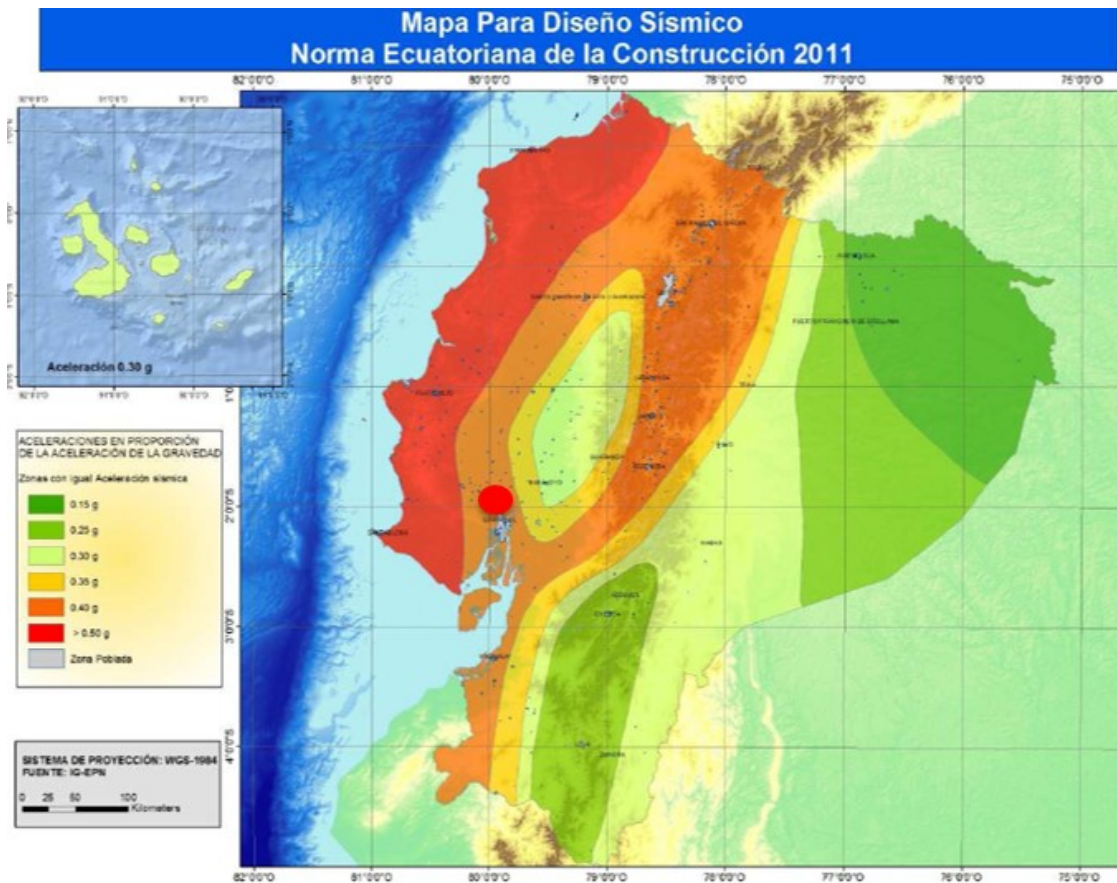
APPENDIX 3: RESPONSE SPECTRAL FORMULATION

Data

| | |
|----------|---------------------------------|
| City | Guayaquil |
| Province | Guayas |
| Region | COSTA (Excluyendo Esmeraldas) |

Parameters

| | |
|-------------------|------|
| Seismic zone | V |
| Z | 0,4 |
| Seismic vulnerab. | ALTA |
| Soil type | E |
| Fa | 1,00 |
| Fd | 1,60 |
| Fs | 1,90 |
| n | 1,80 |
| r | 1,50 |
| To | 0,30 |
| Tc | 1,67 |
| R | 5 |



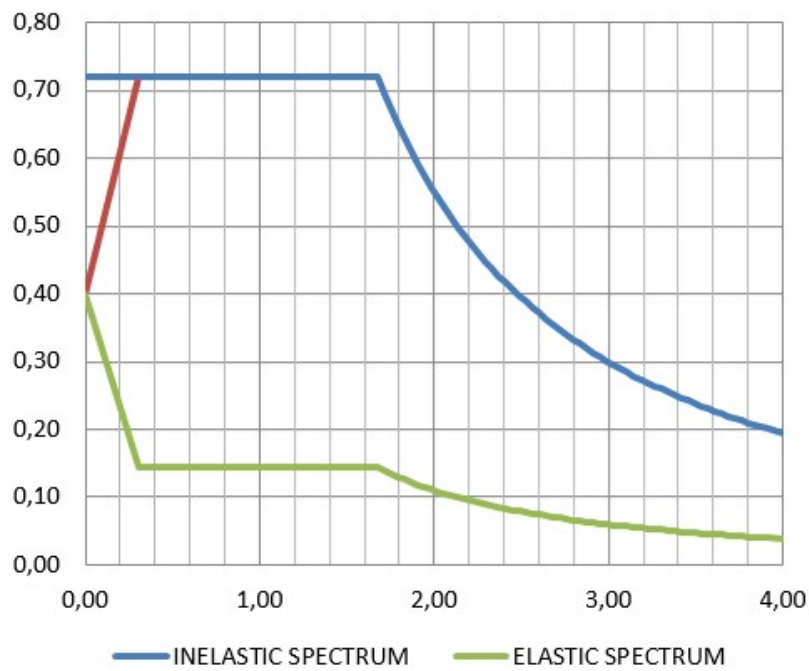
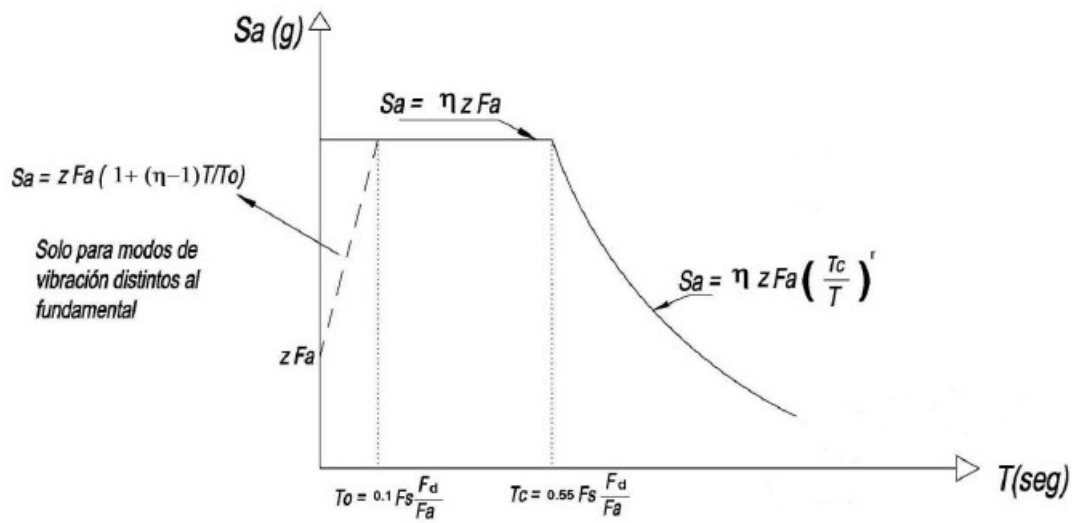


Figure 44 – Acceleration response spectra formulation