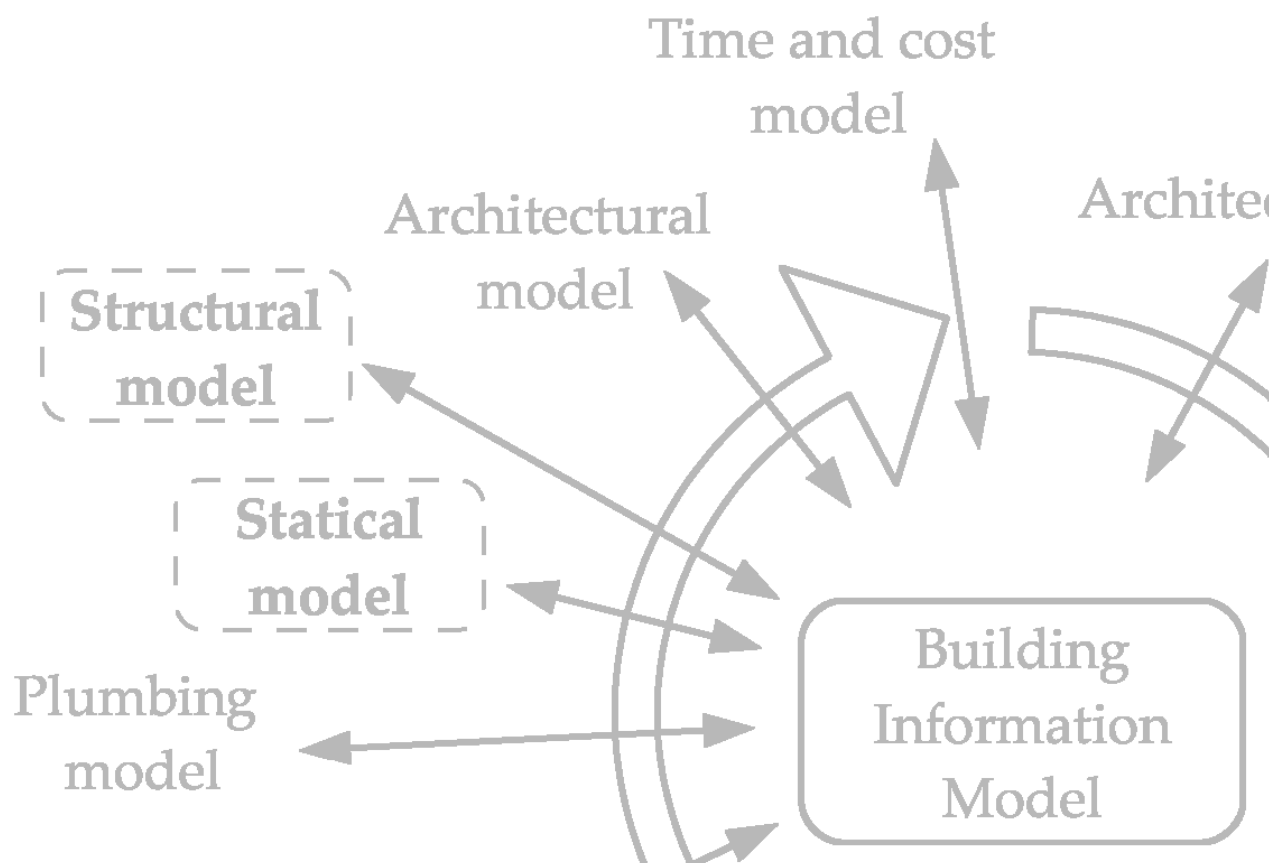


Master's Thesis, June 2010

# Structural modelling and analysis using BIM tools

Master of Science in Civil Engineering  
The School of Civil Engineering, Aalborg University

Anne Kathrine Nielsen & Søren Madsen





**Faculties of Engineering, Science and Medicine**

**The School of Civil Engineering**

Aalborg University

Søhngaardsholmsvej 57

DK-9000 Aalborg

Phone +45 9940 8530

<http://bsn.aau.dk>

**Title:**

Structural modelling and  
analysis using BIM tools

**Theme:**

Master's Thesis

**Project period:**

1<sup>st</sup> of February to the  
9<sup>th</sup> of June 2010

**Made by:**

Anne Kathrine Nielsen  
Søren Madsen

**Supervisor:**

Poul Henning Kirkegaard

**Editions:**

3

**Number of pages:**

81

**Appendices:**

7

**Completed:**

9<sup>th</sup> of June 2010

**Synopsis:**

This study will focus on the structural engineering part in the detail design phase of the building process.

Different S-BIM tools are evaluated through analyses of five structures with varying complexity, different section properties, geometry, material properties and so on.

The S-BIM tools evaluated are:

- Add-on tool for Revit Structure
- Direct link between Revit and Robot
- Direct link between Revit and StaadPro
- Indirect link between Revit and Robot via IFC

The Revit add-on tool tested can be rather useful for calculating section forces and deflection in feasibility studies if a 'load-takedown' feature is introduced.

It is found that the direct links in general are best. Regarding timber structures, the link between Revit and Robot works better than the link between Revit and StaadPro.

The tested IFC exchange file format, IFC Coordination View, was not found suitable for the tests performed in this study.



# Preface

This study is conducted at the 4<sup>th</sup> semester of the Master of Science Programme in Civil Engineering at Aalborg University. The title of the project is *Structural modelling and analysis using BIM tools*. The report has been composed in the period from the 1<sup>st</sup> of February 2010 to the 9<sup>th</sup> of June 2010. The study has been supervised by Associate Professor Poul Henning Kirkegaard.

The authors would like to thank:

- Elizabeth Shulok from Structural Integrators for technical support to the software application *SI Xchange for Revit and STAAD*.
- Rambøll in Aalborg for providing digital models of the House of Music in Aalborg, Denmark.

In extension to this report a CD-ROM containing the employed models is enclosed. In the report the CD-ROM is referred to when relevant. The contents of the enclosed CD-ROM are listed in Appendix A.

References are provided by author and year [Author, year]. The references are listed in the Bibliography as:

- Books: Author. *Title*. Publisher, Year. ISBN.
- Articles: Author. Title. *Journal*, Volume(Number):Pages, Year.
- Web pages: Author. *Title*, Year. URL-address. Date visited.

Aalborg, June 2010

---

Anne Kathrine Nielsen

---

Søren Madsen



# Summary in Danish

Denne rapport er udarbejdet på 4. semester af kandidatuddannelsen i Bygge- & Anlægskonstruktion, Aalborg Universitet. Rapportens titel, oversat til dansk, er:

*Strukturel modellering og analyse ved hjælp af BIM værktøjer*

Denne rapport fokuserer på den strukturelle del af designfasen i byggeprocessen, idet muligheden for udveksling af data, fra den Strukturelle Bygnings Informations Model til konstruktionsingeniørens beregningsværktøjer, behandles. Endvidere vurderes gyldigheden af de, i beregningsværktøjerne, opnåede resultater. I det følgende beskrives indholdet i de enkelte kapitler.

## **Kapitel 1**

I første kapitel gives en introduktion til byggeprocessen og fordelene ved at anvende Bygnings Informations Modellering (BIM) introduceres kort.

## **Kapitel 2**

I andet kapitel uddybes BIM og de to åbne filformater IFC og CIS/2 præsenteres. Desuden introduceres Strukturel Bygnings Informations Modellering (S-BIM). De anvendte S-BIM værktøjer er:

- *Revit add-on tool*: Et strukturelt tilføjelsesprogram i Revit
- *Integration with Robot Structural Analysis*: Et direkte link mellem Revit og Robot
- *SI Xchange for Revit and STAAD*: Et direkte link mellem Revit og StaadPro
- *IFC*: Et åbent filformat, der anvendes som indirekte link mellem Revit og Robot

Kapitlet afsluttes af en problemformulering samt den generelle metode for projektet.

## **Kapitel 3**

I tredje kapitel testes S-BIM værktøjerne vha. tre simple konstruktioner med forskellige tværsnitsegenskaber, geometri, materialeparametre osv. Testene viser at *Revit add-on tool* kun kan anvendes til bestemmelse af snitkræfter og udbøjninger. Linket *Integration with Robot Structural Analysis* giver generelt den bedste overførsel af data, idet linket *SI Xchange* ikke understøtter trækonstruktioner. Dataoverførslen via IFC er meget mangelfuld. Dette skyldes at hverken Revit eller Robot understøtter den strukturelle del af IFC formatet, Structural Analysis View. IFC anvendes derfor ikke til yderligere tests. Ingen af S-BIM værktøjerne er i stand til at håndtere armeret beton, på tilfredsstillende vis, hvorfor der ikke laves yderligere tests med betonkonstruktioner.

---

#### Kapitel 4

I fjerde kapitel testes S-BIM værktøjerne vha. en rammekonstruktion i træ. Konstruktionen er mere kompleks end konstruktionerne i kapitel 3, idet der er flere elementer, som alle er skrå og flere af elementerne er pultbjælker. Ingen af de anvendte S-BIM værktøjer kan håndtere pultbjælkerne. Disse modelleres derfor som stykvise bjælker med konstant tværsnit. *Revit add-on tool* kan stadig kun anvendes til bestemmelse af snitkræfter og udbøjninger. Linket *Integration with Robot Structural Analysis* viser sig igen at være bedre end *SI Xchange*-linket.

#### Kapitel 5

I femte kapitel behandles importen af en model til Revit inden S-BIM værktøjerne testes. Den behandlede konstruktion er en tredimensionel stålkonstruktion, som oprindeligt er modelleret af Rambøll i Tekla Structures. Konstruktionen importeres i Revit via filformaterne DWG, IFC og CIS/2. Ingen af dataoverførslerne giver en tilfredsstillende repræsentation af konstruktionen, hvorfor den i stedet importeres via CIS/2 fra Robot og efterfølgende tilrettes manuelt.

Konstruktionen har en utraditionel form og består af adskillige elementer, hvilket gør den mere kompleks end de tidligere behandlede konstruktioner. De udførte tests viser, at S-BIM værktøjet *Revit add-on tool* ikke kan anvendes til tredimensionelle konstruktioner idet programmet ikke tager hensyn til lasterne fra tilstødende elementer. Heller ikke de direkte links, *Integration with Robot Structural Analysis* og *SI Xchange*, virker efter hensigten i forbindelse med den tredimensionelle konstruktion.

#### Kapitel 6

I sjette kapitel diskuteres resultaterne fra de udførte tests. BIM og anvendeligheden af S-BIM værktøjerne diskuteres. Desuden gives en anbefaling for, hvilken teknologi der er mest hensigtsmæssig i fremtiden.

#### Kapitel 7

Rapporten afsluttes af en konklusion, hvor det vurderes, at selvom de direkte links virker bedst på nuværende tidspunkt, så vil implementering af den strukturelle del af IFC i alle S-BIM og FEM værktøjer være at foretrække i fremtiden.

Til denne rapport hører syv bilag samt en CD-ROM med de anvendte modeller.



# Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Introduction</b>   | <b>1</b>  |
| 1.1      | Introduction to the project . . . . .                       | 1         |
| 1.2      | Layout of the report . . . . .                              | 5         |
| <b>2</b> | <b>Outline of BIM and S-BIM tools</b>                       | <b>7</b>  |
| 2.1      | Building Information Modelling (BIM) . . . . .              | 7         |
| 2.2      | Industry Foundation Classes (IFC) . . . . .                 | 11        |
| 2.3      | CIMSteel Integration Standards (CIS/2) . . . . .            | 17        |
| 2.4      | Structural Building Information Modelling (S-BIM) . . . . . | 18        |
| 2.5      | S-BIM tools . . . . .                                       | 19        |
| 2.6      | Scope of the project . . . . .                              | 23        |
| 2.7      | General method of analysis . . . . .                        | 24        |
| <b>3</b> | <b>Analysis of S-BIM tools – simple structures</b>          | <b>27</b> |
| 3.1      | Introduction . . . . .                                      | 27        |
| 3.2      | Methods of analysis . . . . .                               | 28        |
| 3.3      | Simply supported steel beam . . . . .                       | 29        |
| 3.4      | Simply supported timber column . . . . .                    | 34        |
| 3.5      | Continuous concrete beam . . . . .                          | 37        |
| 3.6      | Subconclusion . . . . .                                     | 43        |
| <b>4</b> | <b>Analysis of S-BIM tools – timber frame structure</b>     | <b>45</b> |
| 4.1      | Introduction . . . . .                                      | 45        |
| 4.2      | Methods of analysis . . . . .                               | 46        |
| 4.3      | Basis of tests . . . . .                                    | 47        |

## CONTENTS

---

|          |  |            |
|----------|--|------------|
| 4.4      | Results of tests . . . . .   | 50         |
| 4.5      | Evaluation of tests . . . . .  | 54         |
| 4.6      | Subconclusion . . . . .  | 55         |
| <b>5</b> | <b>Analysis of S-BIM tools – 3D steel structure</b>                            | <b>57</b>  |
| 5.1      | Introduction . . . . .   | 57         |
| 5.2      | Methods of analysis . . . . .  | 58         |
| 5.3      | Basis of tests . . . . .   | 60         |
| 5.4      | Results of tests . . . . .   | 64         |
| 5.5      | Evaluation of tests . . . . .  | 69         |
| 5.6      | Subconclusion . . . . .  | 70         |
| <b>6</b> | <b>Discussion</b>  | <b>71</b>  |
| 6.1      | BIM as a vision . . . . .  | 71         |
| 6.2      | Applicabilities of current S-BIM tools . . . . .                               | 73         |
| 6.3      | Which technology is most preferable for the future? . . . . .                  | 76         |
| 6.4      | Which process is most preferable for the future? . . . . .                     | 76         |
| <b>7</b> | <b>Conclusion</b>  | <b>79</b>  |
|          | <b>Bibliography</b>  | <b>83</b>  |
|          | <b>Appendices</b>  | <b>87</b>  |
| <b>A</b> | <b>Contents of the enclosed CD-ROM</b>   | <b>A-1</b> |
| <b>B</b> | <b>E-mail correspondence with Elizabeth Shulok from Structural Integrators</b> | <b>B-1</b> |
| B.1      | Questions and answers . . . . .  | B-1        |
| <b>C</b> | <b>Simply supported steel beam</b>   | <b>C-1</b> |
| C.1      | Design parameters . . . . .  | C-1        |
| C.2      | Procedure of tests . . . . .   | C-4        |
| <b>D</b> | <b>Simply supported timber column</b>  | <b>D-1</b> |

|          |  |            |
|----------|--|------------|
| D.1      | Design parameters . . . . .  | D-1        |
| D.2      | Procedure of tests . . . . .   | D-4        |
| <b>E</b> | <b>Continuous concrete beam</b>  | <b>E-1</b> |
| E.1      | Design parameters . . . . .  | E-1        |
| E.2      | Procedure of tests . . . . .   | E-4        |
| E.3      | Procedure of alternatives . . . . .                                    | E-5        |
| <b>F</b> | <b>Timber frame structure</b>  | <b>F-1</b> |
| F.1      | Design parameters . . . . .  | F-1        |
| F.2      | Updated parameters . . . . .   | F-5        |
| F.3      | Procedure of tests . . . . .   | F-7        |
| <b>G</b> | <b>Three-dimensional steel structure</b>                               | <b>G-1</b> |
| G.1      | Design parameters . . . . .  | G-1        |
| G.2      | Procedure of tests for import to Revit from Tekla Structures . . . . . | G-5        |
| G.3      | Procedure of tests . . . . .   | G-6        |



## Introduction

---

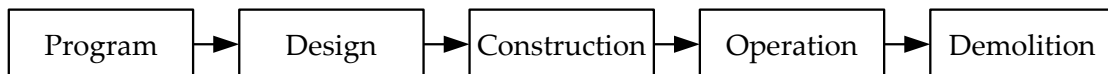
In this chapter the motivation for this study and a brief introduction to the topic of this project is given. Following the layout of the report is presented.

---

### 1.1 Introduction to the project

In the building sector there is a tradition for doing things in the same way as they always have been done. It applies to the construction technique as well as in the building process. Changes happen slowly. Over the past decades computer technology has been implemented to optimize the technical solutions. Currently optimization of the building process using computer technology is ongoing [Linderoth, 2010].

Traditionally the building process is divided into five phases, which is illustrated at Figure 1.1.



**Figure 1.1** *Illustration of the phases in the building process [Bejder and Olsen, 2005, p. 86].*

Each phase in the process is relatively separate from the other phases. A short description of the main activities and participants in the phases is given in the following.

- In the program phase, feasibility studies are made. Moreover specification requirements, schedule and economy for the structure are defined. The participants in this phase are the building owner with his or hers adviser, and possibly the users, and the public authorities.
- In the design phase, the technical solutions are developed and detail drawings are created. This phase is typically partitioned in two sub-phases, a conceptual design phase and a detail design phase. The participants from the program phase are still relevant although architects, engineers and draughtsmen are the dominating participants in this phase.
- In the construction phase, project tracking and management are ongoing contemporary with the construction of the structure. The primary participants are the contractors, but also the architects, engineers, draughtsmen, and building owner can still be active.

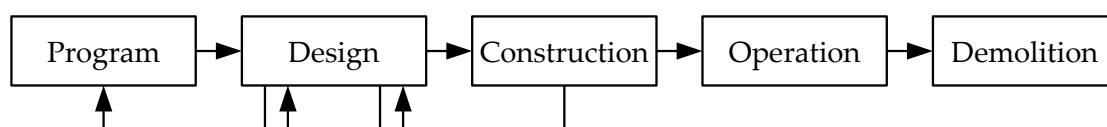
## 1. Introduction

---

- In the operation phase, the dominating activity is that the structure is used for its purpose. In this phase there will be an one and a five year review. The primary participants in this phase are therefore the building owner and the users.
- The demolition phase can be seen as a new process with its own phases. The demolition requires planning and often the participants can be e.g. some other engineers and contractors than those involved in the previous phases.

As described, there are a lot of participants in each phase. Often the participants do their job individually before the next participant take over, e.g. the architect finishes his or her work before the engineer do the calculations. This can be rather time consuming and inexpedient if changes have to be made since several iterations of the process are needed.

One way to make a smoother building process is by making the different phases more integrated as shown in Figure 1.2 where the phases are less separate and the participants solve their tasks more simultaneously. In that connection it can be useful to make use of a common model which contains all the information about a structure.



**Figure 1.2** *Illustration of the integrated building process.*

Information from the program phase can be specification requirements, schedule and economy for the structure. In the design phase information about geometry, materials and other specifications can be added to the model. Under the construction of the structure, information can be changed in the model due to differences between the planned and the actually constructed structure. In the following phases it is easy to get information about the structure because everything is in one place. This can e.g. be useful regarding maintenance, changed use of the structure or addition to the structure.

A model containing all the needed information will be rather comprehensive and several challenges of technological character as well as attitudinal character are connected to the development of such a model. At the present time, no fully developed and flawless technology to create such a model exists, but as described above an optimization of the building process using computer technology is ongoing.

### 1.1.1 Digital Construction

Regarding the use of computer technology in the building process, the Danish government has created the initiative Digital Construction (in Danish: Det Digitale Byggeri) to promote the use of information and communication technology. Digital Construction is developed over a number of years, and the result is ten specific client demands for public building projects. The implementation of the demands started in 2007.

The client demands concern four subjects [Det Digitale Byggeri, 2010a]:

- Procurement, tendering and competitive bidding via the internet
- Application of 3D-models
- Information sharing via the project web of the building project
- Digital assignment of the operation relevant data from the building process to the operation organisation of the building owner

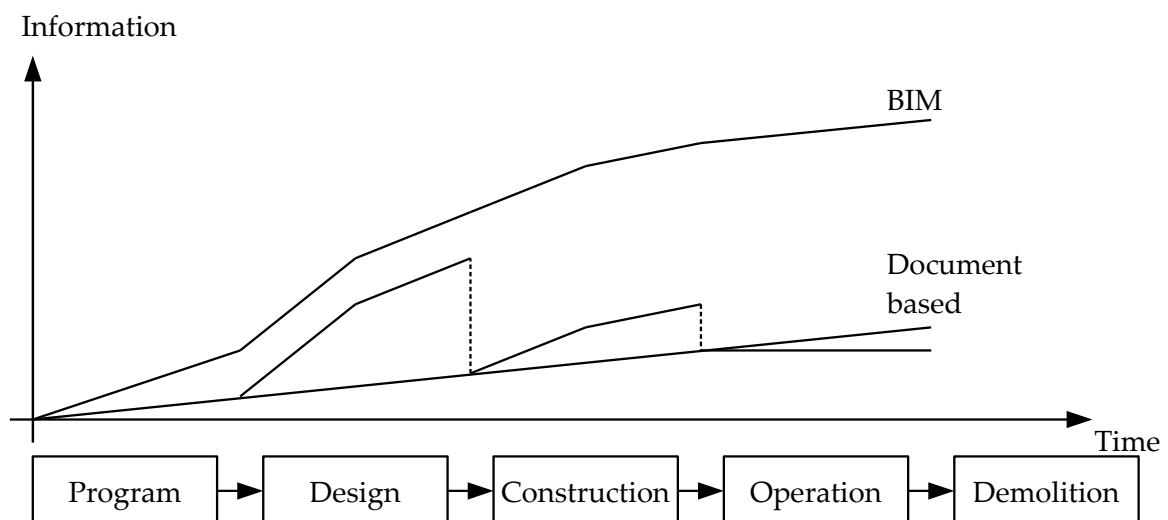
The purpose of the governmental client demands is to enhance the efficiency and quality of construction in Denmark [Det Digitale Byggeri, 2010a].

### 1.1.2 Building Information Modelling in the building process

As described previously, it can be useful to make use of a model which contains all the needed information about a structure, in order to optimize the building process. Such a model can be defined as a Building Information Model. The process of gathering information produced by the architects, engineers, draughtsmen, and contractors among others can be defined as Building Information Modelling.

In this project, Building Information *Modelling* will be referred to as *BIM* and Building Information *Model* will be referred to as *BIM (model)*. The concepts will be elaborated in Chapter 2.

Employing BIM introduces a more integrated building process due to the improved exchange of digital information, compared to the traditional document based exchange of information. Figure 1.3 shows the information flow in the BIM process compared to the document based information flow.



**Figure 1.3** The information flow employing BIM vs. traditional document based information flow. Based on Robinson [2007, p. 520].

As illustrated in Figure 1.3, no information is lost through the phases of the building process in the BIM process.

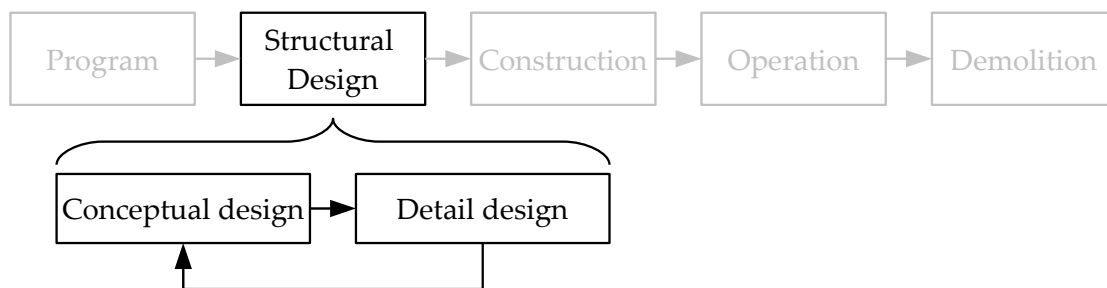
## 1. Introduction

*A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM process to support and reflect the roles of that stakeholder.*

[Edgar and Smith, 2008]

As implied, BIM is relevant for all phases in the building process. The building process includes many different participants and disciplines. E.g. the design phase includes structural design, plumbing design and energy design.

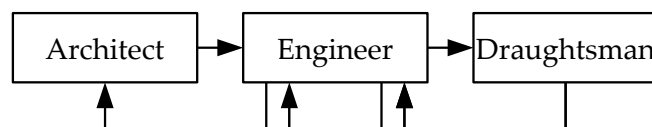
In this project, especially the BIM (model) in connection with the structural design phase is investigated. The structural design phase with its sub-phases is shown in Figure 1.4.



**Figure 1.4** Illustration of the sub-phases in the structural design phase.

The main participants in the structural design phase are architects, engineers and draughtsmen. The architects often dominate the conceptual design phase whereas the engineers and draughtsmen dominate the detail design phase. An efficient structural design phase depends, in particular, on the collaboration and data exchange between the participants.

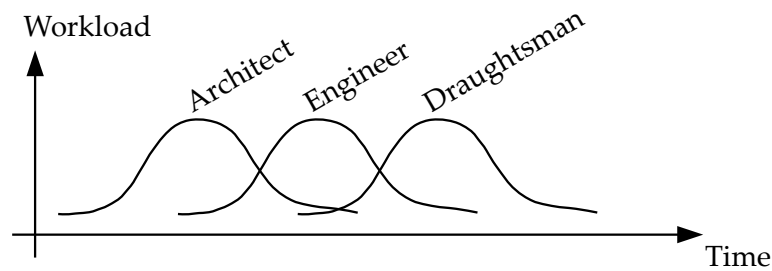
Traditionally the work done by the three participants occur in three relative separate steps staggered in time, starting with the architect and ending with the draughtsman. The traditional structure of collaboration is shown in Figure 1.5.



**Figure 1.5** Traditional structure of collaboration among participants in the structural design phase.

The structure of collaboration shown in Figure 1.5 corresponds with a workflow where the workloads occur in bulges. This is shown in Figure 1.6.





**Figure 1.6** *Traditional workflow, where the workloads are staggered in time.*

A workflow like the one shown in Figure 1.6 might not be the most effective and therefore not preferable.

Recently different structural BIM tools have been introduced. As described previously, this study will focus on the structural engineering part in the detail design phase of the building process. In particular some of these structural BIM tools are tested in order to identify whether or not they can contribute to an optimisation of the traditional workflow shown in Figure 1.6. Before defining the thesis statement, relevant BIM aspects are introduced in Chapter 2.

## 1.2 Layout of the report

After an introduction to this study the layout of the report is presented. The report consists of the following chapters:

### **Outline of BIM and S-BIM tools**

In this chapter a brief introduction to relevant BIM aspects is given and different structural BIM tools are described. This leads to the scope of the project. Finally the general method used in the project is presented.

### **Analysis of S-BIM tools – simple structures**

In this chapter four different S-BIM tools are tested through three rather simple structures with different section properties, geometry, material properties and so on. Further an initial evaluation of the S-BIM tools is given.

### **Analysis of S-BIM tools – timber frame structure**

In this chapter the S-BIM tools are tested through a timber frame structure from Krafthallen in Tromsø, Norway. This structure is chosen to see if the S-BIM tools can handle a rather ordinary structure which is more advanced than the simple structures in the previous chapter.

### **Analysis of S-BIM tools – 3D steel structure**

In this chapter the S-BIM tools are tested through a three-dimensional steel structure from the House of Music in Aalborg, Denmark. This structure is chosen to see if the S-BIM tools can handle a structure which is more advanced than the timber frame structure in the previous chapter.

### **Discussion**

In this chapter the contents presented in the previous chapters are discussed. BIM as a vision and the applicabilities of current S-BIM tools are discussed. Further an evaluation of which technology is most preferable for the future is given.

### **Conclusion**

In this chapter the subjects of this study are summarized and concluding remarks are given.



## Outline of BIM and S-BIM tools

---

In this chapter a brief introduction to the relevant Building Information Modelling (BIM) aspects is given, and different structural BIM tools are described. This leads to the scope of the project. Finally the general method used in the project is presented.

---

### 2.1 Building Information Modelling (BIM)

The original information modelling concept is usually attributed to Codd [1970] where the need for a tree-based hierarchy in which objects are described in a relational view is discussed [Robinson, 2007].

In Object-Oriented Modelling (OOM) the objects can be assigned properties, relationships and behaviour [bips, 2006]. For instance an object or element can possess information about the type of element, material properties and sectional properties as well as the purpose of the element within the structure. Examples of information are:

- Types of elements: Beams, columns, walls, slabs, etc.
- Material properties: Yield stress, modulus of elasticity, shear modulus, density, etc.
- Sectional properties: Height, width, area, moment of inertia, elastic modulus, etc.
- Purpose of the element: Relation to adjacent elements.

In Building Information Modelling (BIM) the objects and elements can possess a number of additional information which is relevant for the participants in the building process e.g. in connection with operation and maintenance.

*Many people associate BIM with a 3D model of an architectural design, but it can be so much more than that.*

[buildingSMART, 2010a]

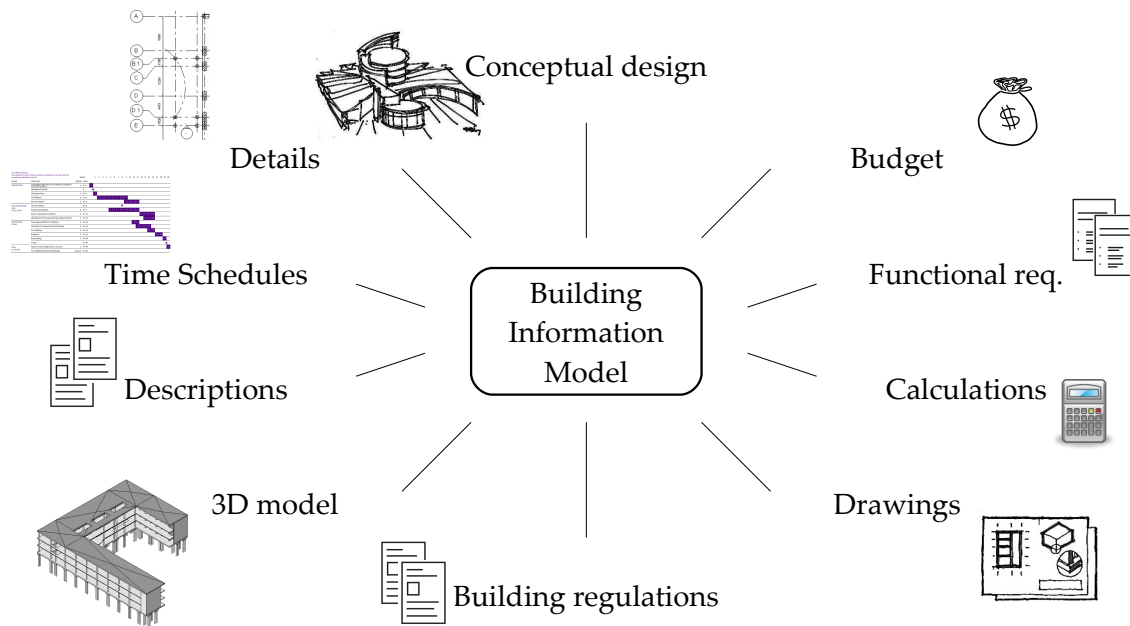
Traditionally economics are referred to as the fourth dimension and time schedules are referred to as the fifth dimension in a BIM (model). Further examples of information which can be included in the BIM (model) are:

- Demands from the building owner
- Descriptions and minutes from meetings
- Input for calculations

## 2. Outline of BIM and S-BIM tools

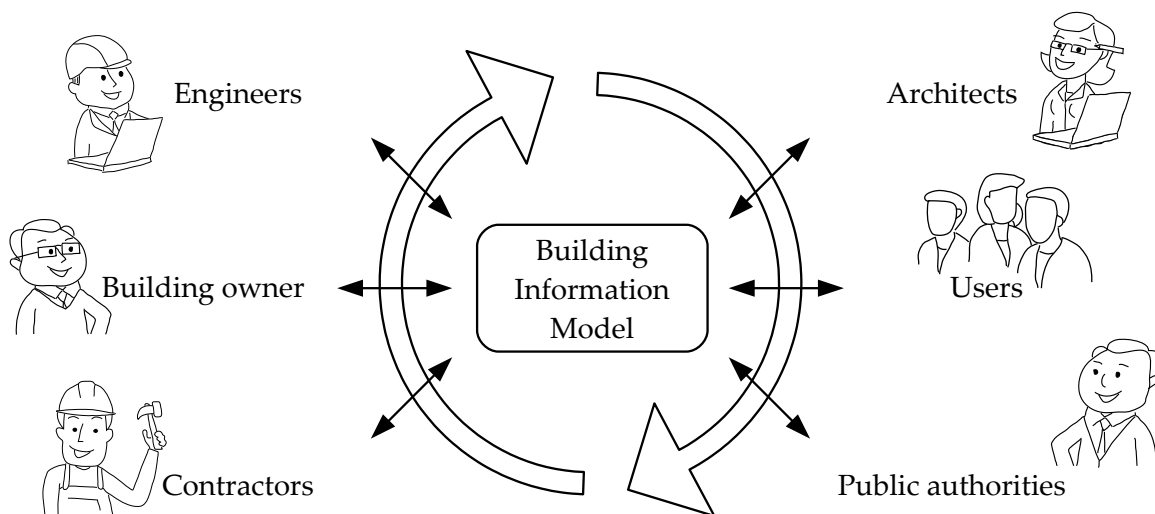
- Drawings and details
- Visualisation and digital coordination
- Basis for facility management

In other words the BIM (model) is a computer representation of the building including both graphical and non-graphical information. An illustration of some of the content in the BIM (model) is shown in Figure 2.1.



**Figure 2.1** The BIM (model) and some of its contents.

BIM implies the employment of the BIM (model), i.e. the integrated process of designing, engineering, constructing and maintaining a building based on the Building Information Model. In other words the BIM (model) is the basis for BIM as a process. Hence the BIM (model) can act as a common workplace for the different participants of the building process as shown in Figure 2.2. This definition of BIM is proposed by Coenders [2009] as “BIM as a vision”.



**Figure 2.2** The BIM (model) and some of the participants of the building process.

One of the purposes of employing BIM is to obtain a better collaboration among the participants and a continuous workflow which occur more simultaneously.

A further objective of BIM is to minimise the redundant re-entering of information. This can be achieved since all the information relevant to the building is gathered in a common model.

Another possible advantage of employing BIM, is to reduce design and construction failures. The different engineering disciplines often have different models. For instance there can be a model with the structural elements, a model with electrical and mechanical installations, a model with heating and ventilation installations and so on. Often different engineers and draughtsmen work together with each discipline. In that connection, a BIM (model), where elements from all the disciplines are gathered, can contribute to reduce design and construction failures, e.g. because of the possibility to check 'clashes' between elements.

In addition to "BIM as a vision" the definition "BIM as a software technology" is proposed by Coenders [2009], where it is argued that the current state of software is far from the vision and it might be plausible that the current software applications are too simplistic. This study will test this statement.

### 2.1.1 Experiences done by others

In Hejnfelt and Øksengaard [2007] interviews of employees in Danish consulting engineering companies, among others, are presented. The interviews are performed in 2007 and indicate the state of the art regarding e.g. BIM at that time. The essence of Hejnfelt and Øksengaard [2007] are described in the following.

- Most of the consulting engineering companies only use 3D-modelling. The architects have started to make some 3D-models and the engineers can design and analyse structures in 3D, but they only do it when it is for the benefit of the project and the building owner [Hejnfelt and Øksengaard, 2007].
- The engineers do not reuse the architects model and they do not use the 3D-models in an intelligent way. It seems like most engineers using 3D still think in lines and not in objects [Hejnfelt and Øksengaard, 2007].
- One engineer states that in principle it would be ingenious if the engineer could get data directly from the architect and could send it directly to the contractor and so on. Another engineer agrees, by stating that exchange and analysis of data should be as automated as possible without loss of quality [Hejnfelt and Øksengaard, 2007].
- In relation to the increased use of 3D-modelling and in the long term the increased use of BIM the interviewed engineers also state some worries. One thinks that BIM will optimise the design phase but points out that the connection to the contractors and suppliers also needs to be improved. Another engineer state that the connection between the architects, engineers and production is alpha and omega but is concerned about the control of analysis and details. Other engineers have similar concerns. They think it is easy to lose perspective and that the true optimal structural design occur less and less often [Hejnfelt and Øksengaard, 2007].

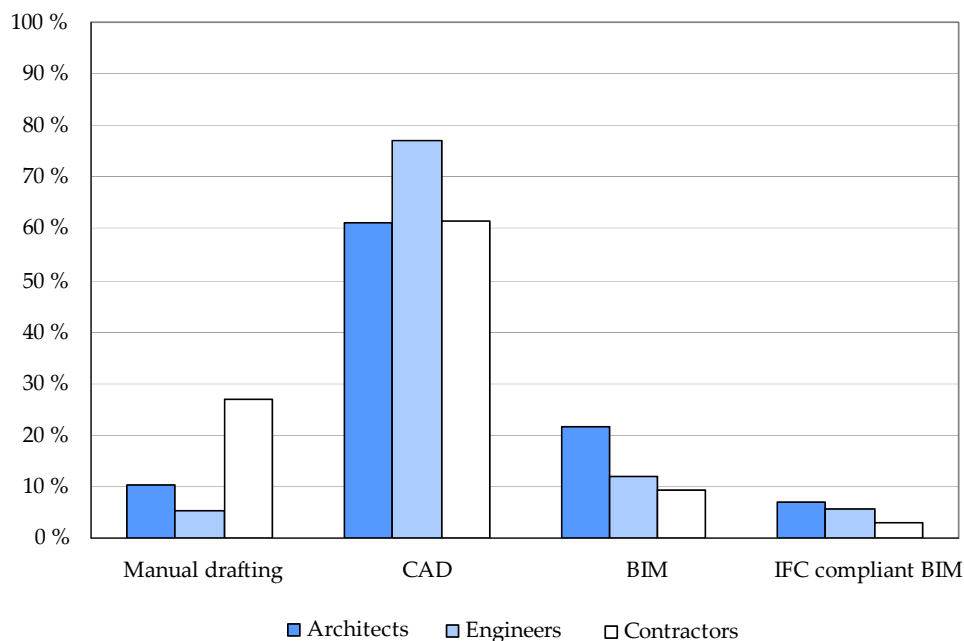
Referring to the interviews it is clear that the application of BIM in practice is far away from "BIM as a vision" proposed by Coenders [2009]. The conclusion of the survey drawn by Hejnfelt and Øksengaard [2007, p. 28] is that the Danish consulting engineering companies in gen-

## 2. Outline of BIM and S-BIM tools

eral have the software to work object orientated but only one of the companies has implemented the structural BIM software.

In Karlshøj et al. [2008] a review of the development and implementation of IFC<sup>1</sup> compatible BIM is presented. The review is among other things based on a survey performed among architects, engineering companies and other relevant companies during the summer 2007. The results presented in this project are valid for the Nordic countries including Denmark, Finland, Norway and Sweden.

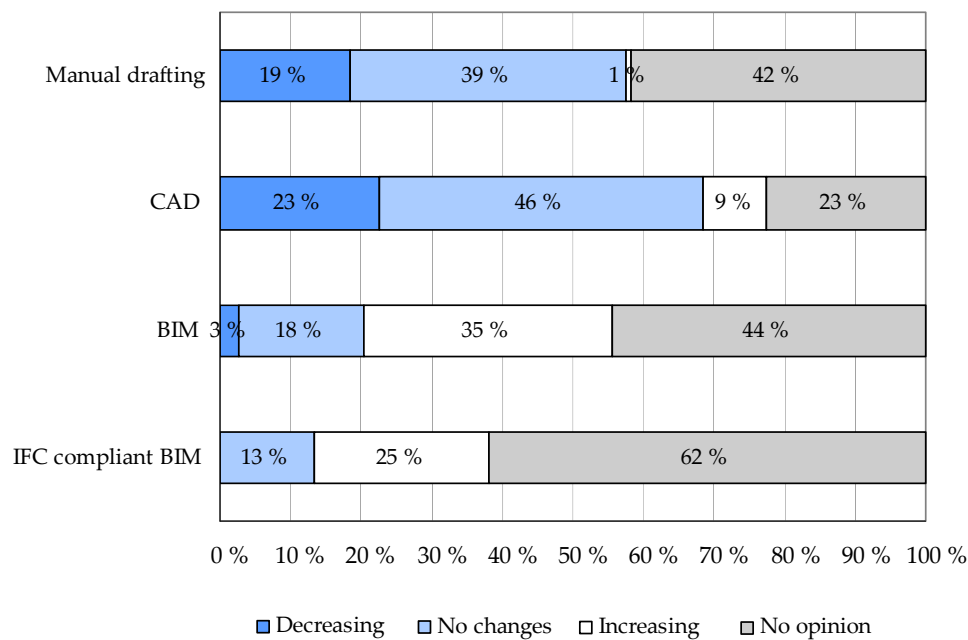
- The results of the survey show that BIM is used in around 20% of projects for architects and in around 10% of projects for engineers and contractors, while the traditional CAD is still the major form of technique used in design work. Further, the results show that manual drafting is used in at least same extent as IFC compliant BIM [Karlshøj et al., 2008]. This is shown in Figure 2.3.
- In the survey the participants were also asked about changes in design work techniques during the last two years, i.e. from 2005 to 2007. The results for the engineers are presented in Figure 2.4 where it can be seen that 35% of the consulted engineers claim that the use of BIM has increased and 25% of the consulted engineers claim that the use of IFC compliant BIM has increased. At the same time the use of manual drafting and CAD as techniques in design work has decreased, according to the consulted engineers [Karlshøj et al., 2008].



**Figure 2.3** Techniques in design work for different disciplines in the Nordic countries. Based on Karlshøj et al. [2008, p. 88].

Please note that all of the above-mentioned is based on surveys performed in 2007, cf. Hejnfelt and Øksengaard [2007] and Karlshøj et al. [2008]. At current it is possible that more of the Danish consulting engineering companies use BIM and IFC compliant BIM. Even if this is the case it will still be relevant with further investigation of BIM.

<sup>1</sup>Industry Foundation Classes. In Section 2.2 further information about IFC is given.



**Figure 2.4** Changes of techniques in design work from 2005 to 2007 for engineers in the Nordic countries. Based on Karlshøj et al. [2008, p. 91].

As the different participants of the building process uses many different kinds of software applications, a common exchange file format is needed in order to keep the information through the entire building process. The internationally acknowledged neutral open standard for exchange of BIM information is defined in the IFC specification. Also the CIS/2 specification is available for the steel supply chain. Both are presented in the following two sections.

## 2.2 Industry Foundation Classes (IFC)

In order to enable a true free flow of information it is not enough only to specify how to share the information. Actually three factors need to be in order [dev.ifd-library.org, 2007]:

1. How to share the information?
2. Which information to exchange and when to exchange the information?
3. What is the information being exchanged?

Re 1) This is defined by the Industry Foundation Classes (IFC) specification, which is elaborated in this section.

Re 2) These information requirements are defined via Information Delivery Manuals (IDMs) and Model View Definitions (MVDs).

The aim of IDM is to specify exactly which information is to be exchanged in each exchange scenario during the building process. It specifies what the process is and its purpose, who the creating and consuming actors are and what the information created and consumed is [Espedokken, 2006].

No software application supports the entire IFC specification. IFC data exchange is achieved with subsets or *views* (MVD) of the complete IFC specification. Each view is

## 2. Outline of BIM and S-BIM tools

---

developed to support one or several data exchange scenarios. The views available are [IfcWiki, 2010b]:

- IFC2x3 Coordination View Version 2.0 – the IFC subset for coordinating the architectural disciplines, building service disciplines and structural disciplines during the design phase of a building project.
- IFC2x3 Structural Analysis View – the IFC subset to exchange the structural analysis model from a structural modelling to a structural analysis application.
- IFC2x3 Quantity Take-off View – the IFC subset to hand over the quantities of a building information model to cost estimation and calculation.
- IFC2x3 Operation & Maintenance View – the IFC subset to handover the facility management relevant information of spaces, furniture, fixture and equipment to Computer-Aided Facility Management CAFM software

Re 3) This is defined through the International Framework for Dictionaries (IFD Library). The IFD standard defines what the objects in the IFC model are, and what parts, properties, units and values they can have [dev.ifd-library.org, 2007].

When these three specifications (IFC, IDM/MVD and IFD) are in place it is possible to have full computerized interoperability between two or more participants of the building process [dev.ifd-library.org, 2007]. IDM/MVD and IFD will not be further elaborated in this study.

The IFC specification is developed and maintained by buildingSMART International (bSI), previously called International Alliance for Interoperability (IAI) [IfcWiki, 2010a].

BIM software applications store the building information in a native and proprietary format. IFC can be used to exchange and share BIM data between software applications developed by different software vendors without the necessity to support numerous native formats. As IFC is an open format, it is neutral and independent of a particular software vendor's schedule and development direction [buildingSMART, 2010a].

*IFC is an open standard to represent, exchange and share the BIM information among different software applications.*

[buildingSMART, 2010b]

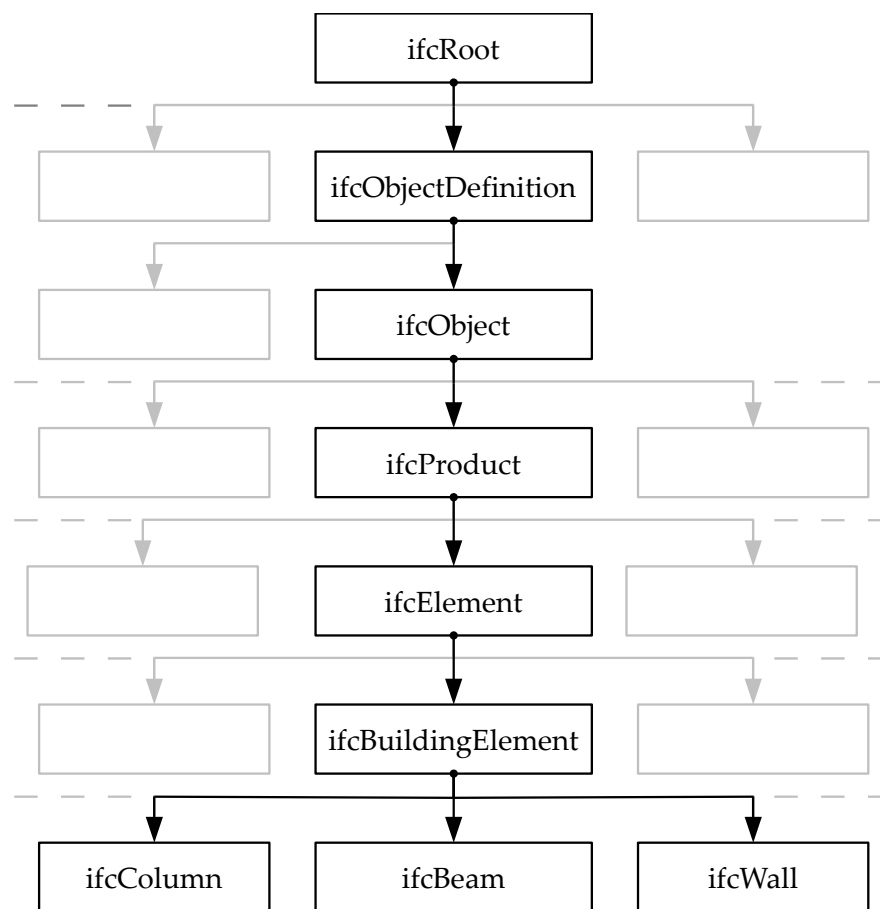
The IFC specification defines a structure of how information about every single object of the building can be defined. This structure divides the building objects in different classes, e.g. ifcBeam, ifcColumn, ifcWall, ifcSlab, and so on, with associated attributes and properties. The different classes can be connected to each other through relations between objects [Det Digitale Byggeri, 2010b].

*Like DXF is the exchange format for CAD drawings, IFC is the exchange format for BIM.*

[Liebich, 2005, p. 5]

The objects or entities in the IFC specification are arranged in a hierarchy structure [Liebich, 2009]. An example of the hierarchy structure of the IFC specification is shown in Figure 2.5.



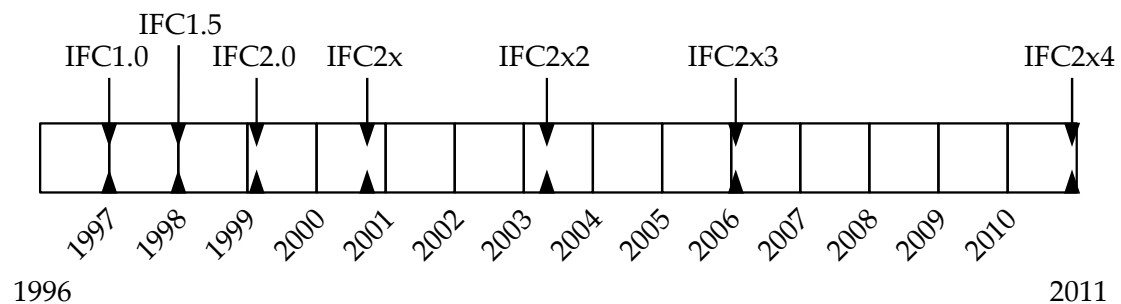


**Figure 2.5** Example of the hierarchy structure of the IFC specification. Based on [Liebich, 2009, p. 46].

Each entity can be assigned properties and information such as geometry, sectional properties, boundary conditions, loads, and so on. This information is either defined directly within the entity or via subtypes or supertypes of the entity.

### 2.2.1 History of IFC

IFC has been developed since 1994. The first specification was released in 1997 and the specification has been expanded ever since. The release history of the IFC specifications is shown in Figure 2.6.



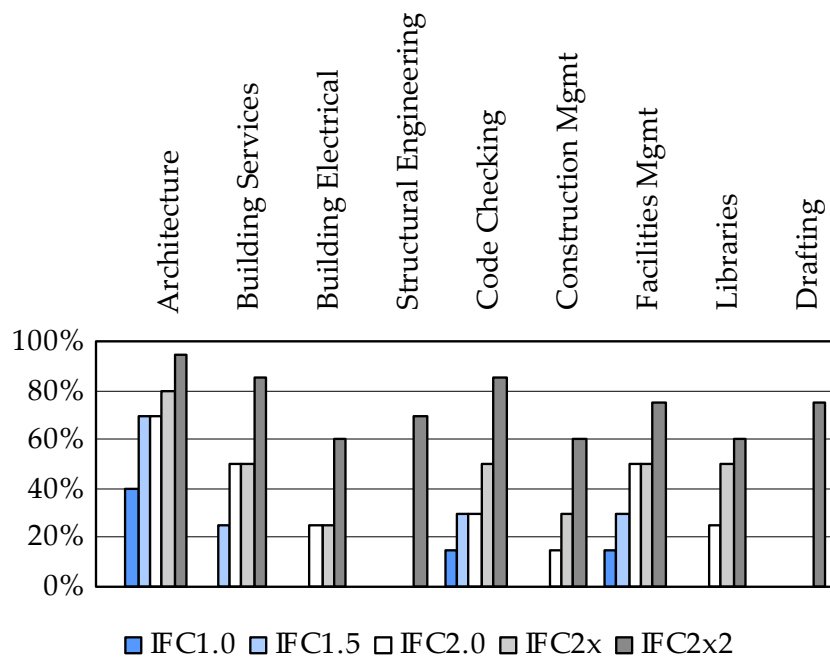
**Figure 2.6** Release history of the IFC specification. Based on buildingSMART [2010f].

For each release more and more options and features have been implemented as shown in

## 2. Outline of BIM and S-BIM tools

Figure 2.7. The first version was developed in relation to architecture, code checking and facilities management. Here code checking should not be thought of as code check cf. Eurocodes but as a check of some general design rules e.g. within fire, ventilation or water systems. Architecture and code check is relevant in the first part of the building process whereas facilities management primarily is used in the last part of the building process cf. Figure 1.2.

In the following versions of IFC e.g. building services and construction management were included. These are also things that corresponds to the first and the last part of the building process, respectively. Finally it can be seen from Figure 2.7 that IFC was developed to include structural engineering and drafting relatively late. This might cause that IFC is not fully developed within these subjects.



**Figure 2.7** Completeness of definitions in the past IFC versions. Based on Liebich [2005, p. 10].

The current release of the IFC specification is IFC 2x3 TC1 where several IFC Extension Projects<sup>2</sup> has been incorporated since IFC version 2x2. The completed extension projects includes [buildingSMART, 2010d]:

- ST-1 Steel Frame Constructions
- ST-2 Reinforced concrete structures and foundation structures
- ST-3 Precast Concrete Construction
- ST-4 Structural Analysis Model and Steel Constructions
- ST-5 Structural Timber Model

<sup>2</sup>IFC Extension Projects are buildingSMART's instrument to research, develop and prototypically implement new features of the IFC data model.

Extension projects for future releases are [buildingSMART, 2010e]:

- ST-6 CIS/2 - IFC Harmonisation
- ST-7 Finite Element Model, Dynamic Analysis Process, and Assignment

In spite of the age long development of IFC and the extensive work conducted in these extension projects, the IFC specification is far from complete.

The next release of the IFC specification, IFC 2x4, will be released at the end of 2010. Some of the essential new features and improvements in IFC 2x4 are [T. Liebich, 2010], [buildingSMART, 2010c]:

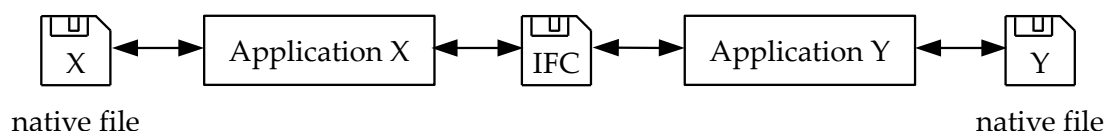
- CIS/2 to IFC harmonisation (ST-6).
- Extended material properties are defined for timber and wood-based materials (anisotropic).
- Enhancement of analysis model. It is possible to provide analysis results not only at point connections but also at curve or surface items.
- Required or provided reinforcement of surface members, e.g. slabs and walls, can now be included.

Since the final IFC 2x4 specification has yet not been released, no implementation in commercial software is available at the moment.

### 2.2.2 Usage of IFC

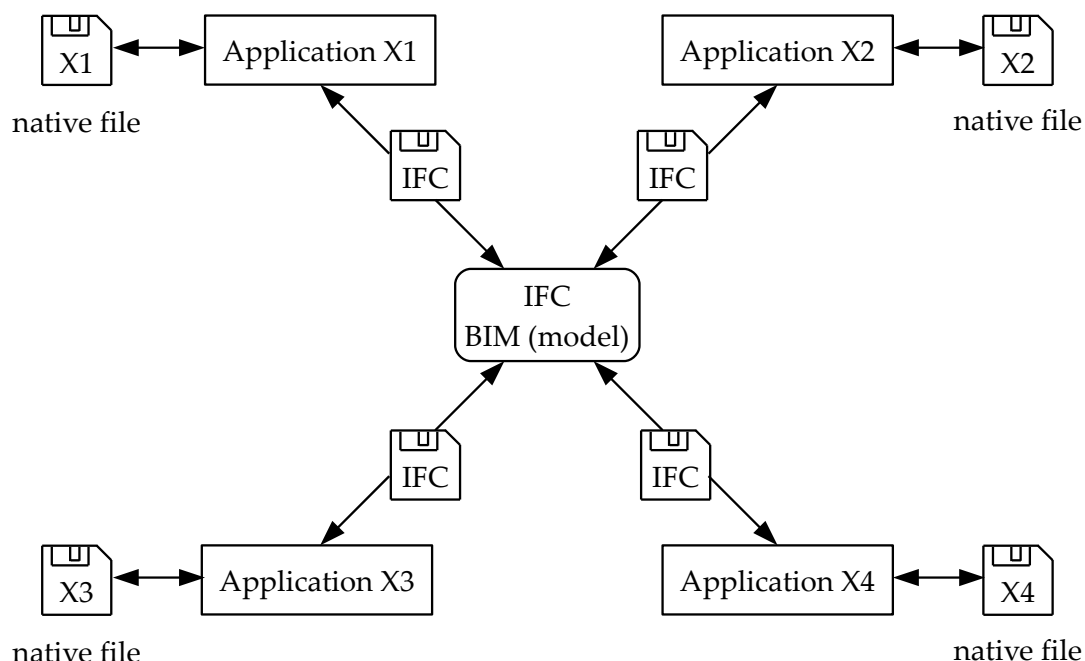
Basically IFC can be used in two ways: Like traditional exchange files or as a central product model in a file archive or on a model server. In both cases, software applications read or write only a subset of the IFC model which must be in accordance with an IFC View definition (MVD).

Using IFC as format of exchange files is shown in Figure 2.8. An IFC exchange file is created using application X and send to import in application Y. The updated IFC file from application Y is then send to merge back in application X.



**Figure 2.8** Using IFC as format of exchange files. Based on Osterrieder and Richter [2005, p. 7].

Using IFC as a central BIM (model) is shown in Figure 2.9. In principle the content of the central BIM (model) is the *sum* of information provided by each participant. But due to the synergy effect of the integrated building process, the content is the *combination* of all the contributed information.



**Figure 2.9** Using IFC as a central BIM (model). Based on Osterrieder and Richter [2005, p. 8].

In this study IFC will be used as format of exchange files.

### 2.2.3 Experiences done by others

With regard to data exchange the interviews performed in 2007 and presented in Hejnfelt and Øksengaard [2007] indicate that engineers see both pros and cons in IFC.

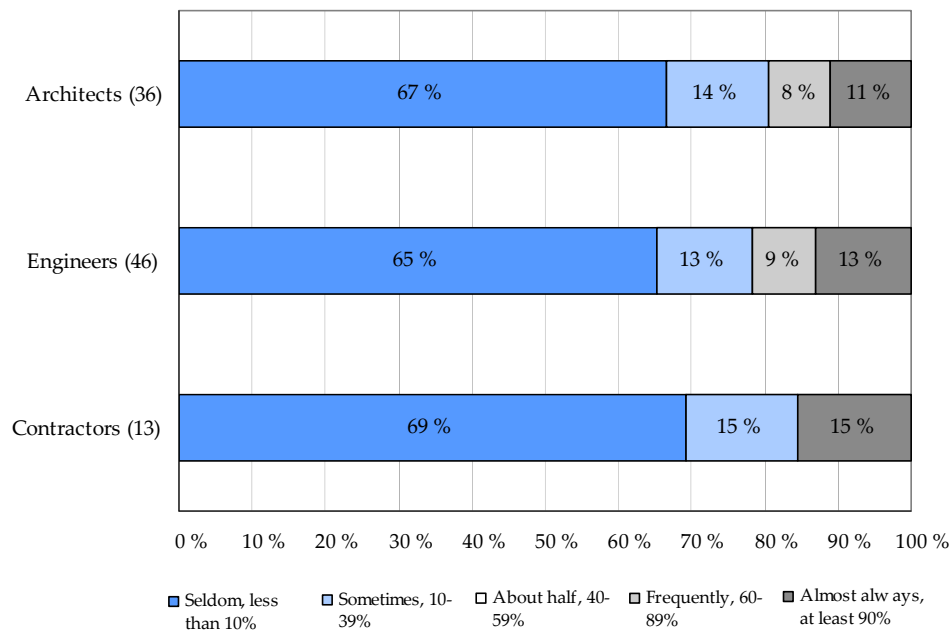
- None of the interviewed engineers disagree that an independent and neutral file format for data exchange is necessary. Many of them see IFC as the best open file format, but they also agree that IFC is not good enough yet. The problem with data exchange is that data is lost every time an exchange is made. In that connection more of the interviewed engineers mention that IFC is a relative low or maybe the lowest common denominator [Hejnfelt and Øksengaard, 2007].
- In relation to IFC it is important to remember that data exchange can occur at different levels. E.g. it can be from an architectural BIM application to a structural BIM application or it can be from BIM applications to FEM applications. Several of the engineers mention a direct link<sup>3</sup> as the best solution for intern data exchange because a direct link has more possibilities and thereby can be a higher common denominator for related software applications. In return they see IFC as the best solution for external data exchange because IFC is good for data exchange between collaborators with different types of software applications. Thus, both the direct link and IFC is needed [Hejnfelt and Øksengaard, 2007].

The conclusion of the survey drawn by Hejnfelt and Øksengaard [2007, p. 28] is that the Danish consulting engineering companies in general do not use integrated design and consequently neither direct link nor IFC.

<sup>3</sup>Further information about direct linking is given in Section 2.5.2.

As described previously Karlshøj et al. [2008] has made a review of the development and implementation of IFC compatible BIM.

- According to their survey the amount of exchanges based on IFC are rather low. In Figure 2.10 it is shown that 65% of the engineers seldom use IFC in BIM exchanges. Only 13% almost always use IFC in BIM exchanges. The tendency is almost the same for architects and contractors [Karlshøj et al., 2008].



**Figure 2.10** Part of BIM exchanges based on IFC for different disciplines in the Nordic countries. Based on Karlshøj et al. [2008, p. 100].

Please note that the above-mentioned is based on surveys performed in 2007, cf. Hejnfelt and Øksengaard [2007] and Karlshøj et al. [2008]. The use of IFC may have increased during the last three years. However, the development of IFC is an time demanding and on going process, thus the comments about IFC are still relevant.

## 2.3 CIMSteel Integration Standards (CIS/2)

An alternative to IFC is CIS/2 which is developed for the planning, design, analysis and construction of steel framed buildings and similar structures [CIMsteel, 2003]. CIS/2 was developed by Andrew Crowley and Alastair Watson at the Steel Construction Institute, UK [NIST, 2010]. CIMsteel stands for the Computer Integrated Manufacturing of Constructional Steelwork [CIMsteel, 2003].

CIS/2 is a set of specifications that enables mutually compatibility between software applications for steel structures. This enables exporting data from one application into another. The CIS/2 documentation specifies which information to exchange between software applications, and how the information must be structured in a data exchange file (\*.stp) or a model repository.

The CIS/2 specification is intended to create a smooth and integrated information flow between all participants involved in the steel construction supply chain.

CIS/2 has been implemented as a file import or export capability by many steel design, analysis, engineering, fabrication, and construction software applications [NIST, 2010]. A CIS/2 file exported by an analysis or design software application could be imported into a detailing software application to detail the connections. Like IFC, CIS/2 is not a software package. The user will see CIS/2 as a file format to import or export data in a steel related software application.

The CIS/2 standard covers everything from nuts and bolts to materials and loads to frames and assemblies. Structures can be represented as analysis, design, or manufacturing models [NIST, 2010].

The use of CIS/2 as well as IFC is an essential part of improving the delivery of structural steel projects in the steel supply chain [NIST, 2010]. It can help minimising the redundant re-entering of information. Interoperability between different software applications using CIS/2 and IFC is also a essential part of BIM.

### 2.4 Structural Building Information Modelling (S-BIM)

The structural engineering part of BIM is given the acronym S-BIM by Hejnfelt and Øksengaard [2007]. This will also be used in this study.

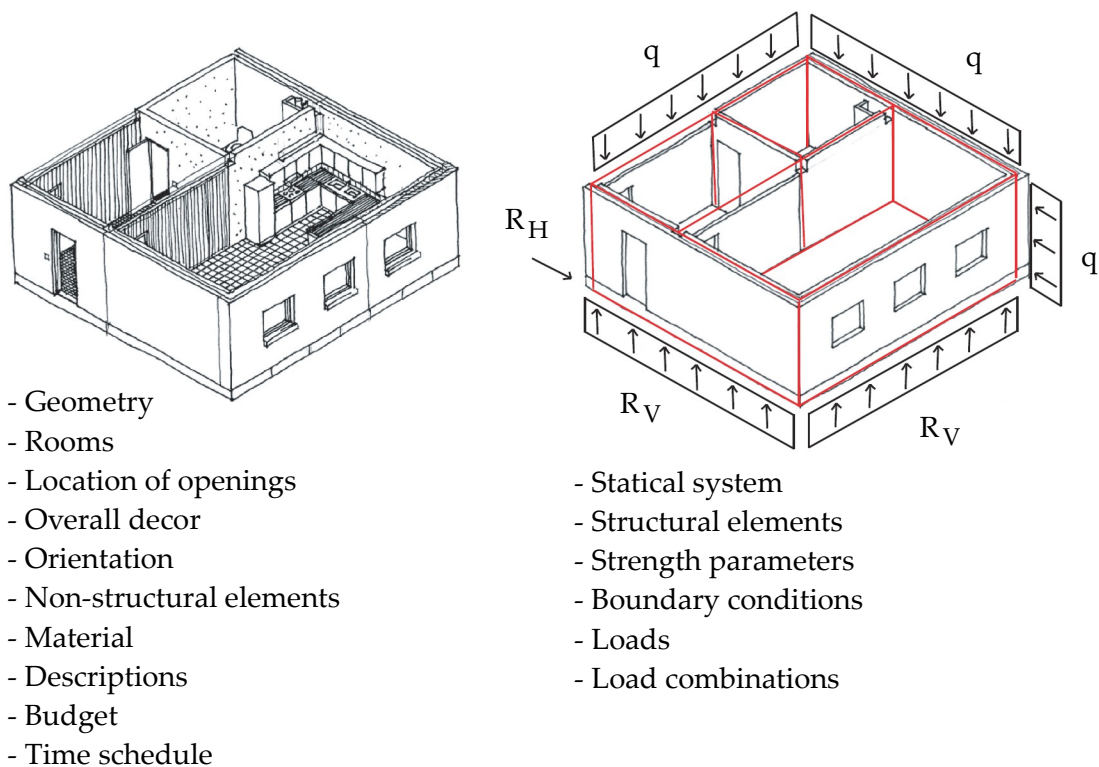
The architects typically focus on the artistic expression of the structure and the interaction between the structure and the environment in every sense. Some architect models therefore only show surfaces of the structure and do not contain information about e.g. structural elements. Architects work with space, mass texture and shapes. I.e. they work with objects in another way than engineers work with building objects in the S-BIM [Robinson, 2007, p. 522].

The architect models are a part of the BIM (model). This means that even though the content of the architect and S-BIM (models) can be very different, the architect models indirectly form the basis of the S-BIM (models).

S-BIM being a subset of BIM can possess the necessary information for structural engineers. I.e. loads, load combinations, geometry, boundary conditions, material properties, sectional properties, and so on. Hence S-BIM can be used for structural analysis as well as drawing and report production [Robinson, 2007].

A simple example of the difference between BIM and S-BIM is shown in Figure 2.11. The BIM (model) includes information about geometry, rooms and location of openings which e.g. is relevant to the architect. Further, information about the overall decor and the orientation of the building which e.g. is relevant to the HVAC engineer is included. Additional, information about non-structural elements and materials which e.g. is relevant to the structural engineer is included. Finally, the BIM (model) includes budget and time schedules which e.g. is relevant to the building owner.

In the S-BIM (model) information about the statical system, structural elements, strength parameters and so on are included. This information is added by the structural engineer and is only relevant to the structural engineer.



**Figure 2.11** Left: BIM (model). Right: S-BIM (model). Note that this is a very simple example, where only a few loads and centre lines are shown. Based on bips [2006, p. 39].

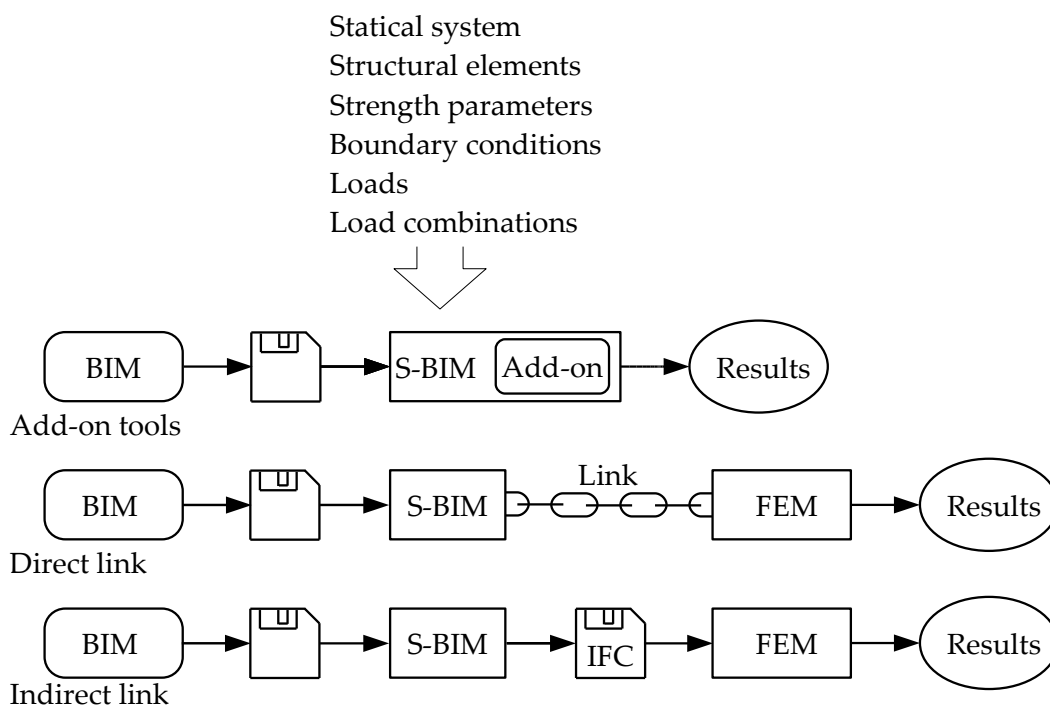
## 2.5 S-BIM tools

The BIM (model) – containing information from many participants of the building process – is handed over to the structural engineer, e.g. via the IFC format. In the S-BIM software the engineer can assign relevant information to the model. This can be specific information about e.g. geometry, material properties, loads and boundary conditions, which e.g. the architect did not define. From the S-BIM software the engineer can perform structural analysis through structural BIM tools.

In this project the S-BIM tools are defined as structural add-on tools to the S-BIM software, direct links or an indirect link from the S-BIM software to traditional FEM software.

The information flows from the BIM (model) to the results of the calculations are shown in Figure 2.12 where BIM refers to the BIM (model), S-BIM refers to the structural BIM software, FEM is the analysis software whereas Results can be e.g. coefficients of utilisation and deflections.

## 2. Outline of BIM and S-BIM tools



**Figure 2.12** The information flow from the BIM (model) to the results of calculations.

In Figure 2.12 the process with structural add-on tools is shown in the top. This process gives the most direct information flow from S-BIM to the results. The process with a direct link is shown in the centre and the process with an indirect link e.g. via IFC is shown in the bottom. These processes contain an extra step compared to the process with the add-on tools.

In the integrated design process the changes to the structure obtained from the results of the structural analysis are updated in the S-BIM and subsequently in the BIM.

In relation to Figure 2.12 different types of software can be used in the different phases. Examples of S-BIM software are Tekla Structures and Autodesk Revit Structure. In this project *Autodesk Revit Structure 2010* [Autodesk, 2010a] is used. The main argument for this is that Revit Structure has some interesting structural add-on tools.

Examples of FEM software which can be used for analysis and design in relation to BIM are Bentley StaadPro and Autodesk Robot Structural Analysis. In this project both *Bentley StaadPro V8i* [Bentley, 2008] and *Autodesk Robot Structural Analysis Professional 2010* [Autodesk, 2010b] are used. The reason for this is that these applications are widely used in consulting engineering companies in Denmark. Additionally, there is a direct link from Revit Structure to Robot Structural Analysis. Using Robot Structural Analysis makes it possible to test both this direct link and the indirect link. On the other hand, StaadPro is interesting in relation to testing the direct link between two software applications from different software vendors.

In this study the following abbreviations are used:

- *Autodesk Revit Structure*: Revit or RVT
- *Autodesk Robot Structural Analysis Professional*: Robot or RSA
- *Bentley StaadPro*: StaadPro or SPro

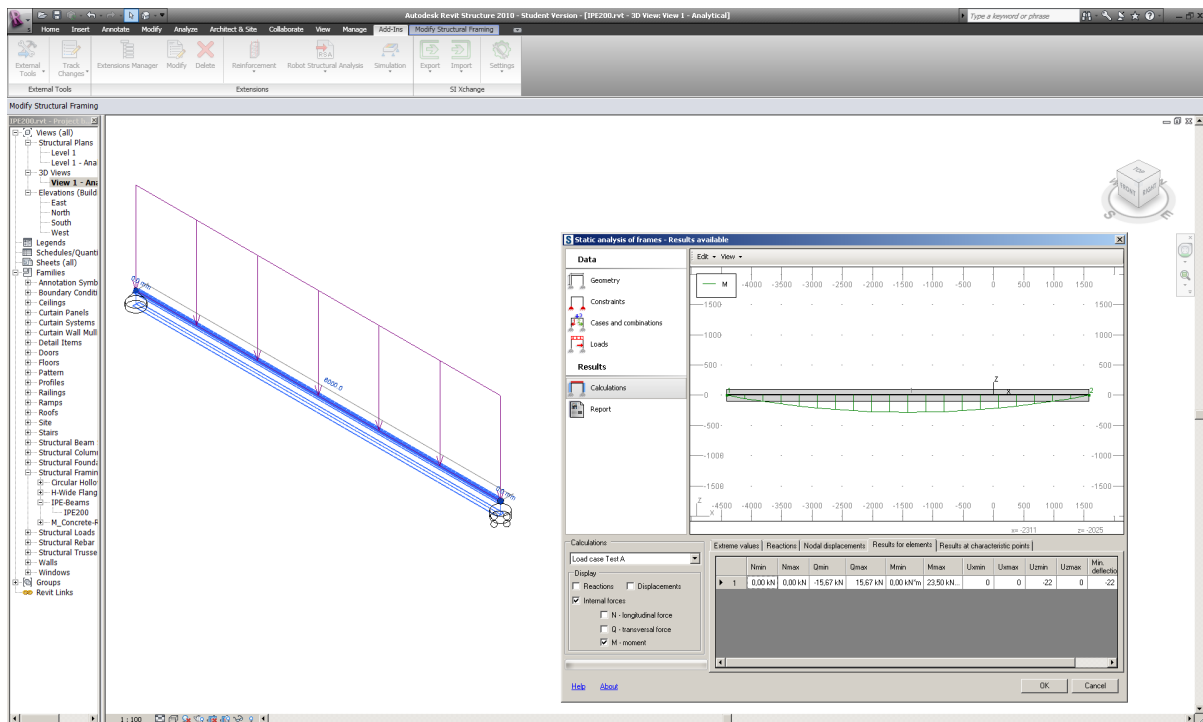


The structural add-on tools, the direct link and the indirect link are elaborated in the following.

### 2.5.1 Add-on tools for S-BIM software

As described, the employed S-BIM software in this project is Revit Structure 2010. The official structural add-on tools for Revit Structure are *Revit Extensions for Autodesk Revit Structure 2010* [Autodesk, 2010c].

Add-on tools are defined as extended features in the S-BIM software which enables analysis of structures inside the S-BIM software. An example is shown in Figure 2.13 where the Revit Structure extension *Simulation - Static Analysis of Frames* is used to calculate section forces on a beam.



**Figure 2.13** Screendump from the Revit Structure extension Simulation - Static Analysis of Frames.

If the possibilities of analysis via the add-on tools are satisfactory and reliable the analysis can be performed without traditional FEM software. This can make the design phase less complicated for the structural engineer who has to be confidential with fewer applications. The add-on tools for Revit Structure enable the user to be more productive while working on projects.

Another possible benefit of the add-on tools is that they are developed from scratch by contrast to traditional analysis software applications, which typically are developed for steel structures originally, and then adapted to other materials as timber and reinforced concrete.

In this study the employed add-on tool is [Autodesk, 2010c]:

- Revit Structure extension *Simulation - Static Analysis of Frames*: Revit add-on tool

## 2. Outline of BIM and S-BIM tools

---

This add-on tool enables static analysis of a 2D frame defined in Revit Structure. It employs information from Revit Structure such as: frame geometry, frame members, boundary conditions, loads and load combinations.

In this project the results from the Revit add-on tool are compared with other methods of analysis. Thereby the applicability of the structural add-on tool is evaluated.

In addition to the add-on tool described above, the Revit Extensions provides a wide range of tools enabling e.g. structural analysis, modelling of concrete reinforcement, interoperability and construction documentation. The features from Revit Extensions used in this study are mainly within the area of structural analysis and interoperability, since this is the focus of the study. The employed Revit Extensions are [Autodesk, 2010c]:

1. Robot Structural Analysis - Integration with Robot Structural Analysis
2. Robot Structural Analysis - Reinforcement Design
3. Import/Export - CIS/2 Import

Re 1) This extension facilitates a bi-directional integration of Revit Structure and Robot Structural Analysis. It enables dynamic import and export of data between the two software applications.

Re 2) The extension enables design of reinforcement in Robot for a reinforced concrete structure element modelled in Revit Structure.

Re 3) This extension facilitates import of CIS/2 files created in other software applications.

### 2.5.2 Direct link

A direct link is defined as a link between two software applications e.g. via an Application Programming Interface (API). The API is an interface implemented by a software application to enable interaction with other software applications, in this study the direct link must enable interaction between S-BIM software and FEM software.

An example of a direct link is the link *Integration with Robot Structural Analysis* between Revit and Robot provided in Revit Extensions for Autodesk Revit Structure 2010. Another direct link used in this study is *SI Xchange for Revit and STAAD* [Structural Integrators, 2010] which enables data exchange between Revit and StaadPro. This link will be referred to as *SI Xchange* in this report. In this study the direct links are used for the same structural analysis as the structural add-on tool and the results are compared to make an evaluation of which methods are best.

Cf. Appendix B.1 there are some limitations of the current version of *SI Xchange*. These are:

- The link only supports steel and concrete materials
- Changes of boundary conditions in StaadPro are not currently sent back to Revit
- Only size changes and column rotations of elements in StaadPro are being updated in Revit

The tests performed in this study will show the results of these limitations.

### 2.5.3 Indirect link

An indirect link has the same function as a direct link namely to transport the needed information from the S-BIM software to the FEM software. The difference between the direct and the indirect link is that the direct linking occurs via a proprietary file format whereas the indirect linking occurs via an independent and natural file format, like IFC.

In this project the IFC file format is used to exchange data between Revit and Robot. This is done to evaluate the applicability of the IFC format compared to the direct link.

Note that Revit Structure only supports the IFC2x3 Coordination View which might introduce some limitations for the tests performed in this study, compared to if the IFC2x3 Structural Analysis View was supported. Cf. Section 2.2, the IFC Coordination View is intended for coordinating the architectural disciplines, building service disciplines and structural disciplines during the design phase of a building project. Thus it might not be optimal for data exchange of the structural analysis model from a structural modelling to a structural analysis application, which the IFC Structural Analysis View is intended for.

The tests performed in this study will show the results of these limitations.

## 2.6 Scope of the project

This study will focus on the structural engineering part of the detail design phase in the building process. Based on the experiences in this chapter it is found, that in general the Danish consulting engineering companies have the software to work object orientated, but they do not use integrated design and consequently neither direct link nor IFC. This might be due to limitations of the current S-BIM tools. Thus, the thesis statement reads:

*What are the strengths and limitations in the current (a) add-on BIM tools, (b) direct links between S-BIM and FEM applications, and (c) IFC exchange file format, and which technology is most preferable for the future?*

Different possibilities of implementing structural analysis in the S-BIM tools and the possibilities of exchanging data between S-BIM and FEM applications are evaluated. This is done by tests of structures divided in three parts:

1. Simple structures with different section properties, geometry, material properties and so on
2. A timber frame structure from Krafthallen in Tromsø, Norway
3. A three-dimensional steel structure from the House of Music in Aalborg, Denmark

The different methods of analysing the structures are:

- Structural analysis via the Revit add-on tool
- Structural analysis in Robot via the link between Revit and Robot
- Structural analysis in StaadPro via the link between Revit and StaadPro
- Structural analysis in Robot via IFC

When possible the structural analysis includes code checking cf. Eurocodes. The results obtained are compared with results obtained by traditional structural analysis methods. Thereby the S-BIM tools are evaluated.

To answer the thesis statement, different methods of analysis are used.

### 2.7 General method of analysis

In this section the general applied methods will be presented. In each chapter the relevant methods will be elaborated.

In order to answer the thesis statement, tests of different structures are performed. The tests sets of in a positivistic approach which consists of the following:

- Construct a hypothesis: The structures are chosen to show the possibilities and to reveal the lacks of the S-BIM tools. For each structure the expectations to the tests and the results of the test are considered.
- Perform the test: For each structure the S-BIM tools are tested systematic. The results are collected and stored schematic.
- Evaluate the results of the test: The results of the tests are compared to the expectations and an evaluation of the S-BIM tools is given.

Based on the evaluations of the tests, the authors will give its recommendations for the future work regarding the usage of S-BIM tools in the building process.

As described in Section 2.6 the first tests treat simple structures with different section properties, geometry, material properties and so on. The purpose of firstly testing the S-BIM tools by means of simple structures is to make some tests which are expected to work with no or few errors. Furthermore the simple tests will contribute to an initial overview of the possibilities and limitations in the S-BIM tools and the methods used in the S-BIM and FEM applications. Based on the tests performed for the simple structures the basic properties of the S-BIM tools are determined.

For the next structures – a timber structure from Krafthallen in Tromsø and a steel structure from the House of Music in Aalborg – the complexity is increased gradually. The purpose of this is to investigate the possibilities of the S-BIM tools when the structures have e.g. varying cross section and a non symmetric geometry.

#### 2.7.1 Guideline for test evaluations

The applicability of the S-BIM tools are evaluated in each chapter. The evaluations are based on a grading scale consisting of stars where five stars are best. The meaning of the stars is given in the following:

☆ ☆ ☆ ☆ ☆

Zero stars are given for a very low performance of the S-BIM tool.

★ ☆ ☆ ☆ ☆

One star is given to the S-BIM tool which makes it possible to determine section forces and deflection.

★ ★ ☆ ☆ ☆

Two stars are given when it is possible to transfer almost all the necessary information from the S-BIM software to the FEM software.

★ ★ ★ ☆ ☆

Three stars are given when it is possible to transfer all the necessary information from the S-BIM software to the FEM software. However it is not possible to transfer any information backwards.

★ ★ ★ ★ ☆

Four stars are given when it is also possible to transfer some of the necessary information backwards from the FEM software to the S-BIM software.

★ ★ ★ ★ ★

Five stars are given when it is possible to transfer all the information forward and backwards from the S-BIM software to the FEM software.

A more thorough explanation will be given at each evaluation.

### 2.7.2 Source criticism

In order to get information which can support the understanding of the topics in this project different sources are applied.

A basic knowledge of BIM is obtained via scientific articles and websites of organisations within this area. Further state of the art within structural BIM is, among other things, obtained via study of two master's theses from DTU. In order to understand the applied software applications the manuals and websites of the applications have been used. The results of the performed tests are evaluated according to Eurocodes.

The scientific articles are produced by a scientists or a group of scientists who have a huge knowledge within the topic of the article. Typically the content of the articles are substantiated by several years of research, experiments and/or calculations. The articles are not necessarily objective but they are considered reliable.

Examples of concepts which are relevant in connection with BIM are *buildingSMART* and *Digital Construction* (in Danish: Det Digitale Byggeri). Behind *buildingSMART* are a number of international committees working for development and implementation of the concept in different ways. Behind *Digital Construction* is the network of implementation (in Danish: Implementeringsnetværket) consisting of a number of Danish organisations within construction. The aim of the organisations is to promote the building process by use of for instance BIM. The concepts are relevant in order to understand the development of BIM so far and in the future.

The two master's theses from DTU are produced by Hejnfelt and Øksengaard [2007] and Pilgaard and Jonathan [2010], respectively. In Hejnfelt and Øksengaard [2007] a number of interviews are presented. These can contribute to awareness about state of the art within BIM, although interviews and the interpretation of these are subjective.

The manuals and websites of the software applications have been investigated in order to gain insight of the possibilities with the applications. The manuals are technical documents with instructions which can support the use of the applications. These are assumed to be objective. As opposed to this the websites are subjective since they besides to inform about the applications also should sell them.

The calculations in this project are performed according to Eurocodes since these are the valid European standards. Eurocodes are produced by experts with several years of experience and the methods presented in these standards are considered reliable. However, the specific choice of calculation methods is not essential in this project as long as the software applications are able to handle calculations with a given complexity and that the software applications employ the same methods.

### 2.7.3 Employed software applications

In the following a short description of the employed software applications is given. Note that the descriptions are based on the websites of the software vendors.

*Autodesk Revit Structure* is a S-BIM software application for structural engineering. The application provides tools for structural design and analysis [Autodesk, 2010a]. In Revit Structure both a physical and an analytical model is combined to represent the structure. The physical model is used as basis for drawings and coordination while the analytical model is used for structural analysis in another software application.

*Autodesk Robot Structural Analysis* is a FEM software application for structural engineers. Interoperability with Autodesk Revit Structure software extends the BIM process, enabling engineers to more quickly perform comprehensive building and engineering analysis on a variety of structures [Autodesk, 2010b].

*Bentley StaadPro* is a FEM software application which allows structural engineers to analyse and design virtually any type of structure of steel, concrete, timber, aluminium and cold-formed steel [Bentley, 2008].

*Column and beam design* from NordSoft ApS is a software application which enables structural engineers to design reinforced concrete beams and columns according to DS/EN 1992-1-1 [2008] either by means of elasticity or plasticity [Rasmussen and Rasmussen, 2010].

## Analysis of S-BIM tools – simple structures

---

In this chapter, the four S-BIM tools, presented in Section 2.6, are analysed through three rather simple structures, and an initial evaluation of the S-BIM tools are given.

---

### 3.1 Introduction

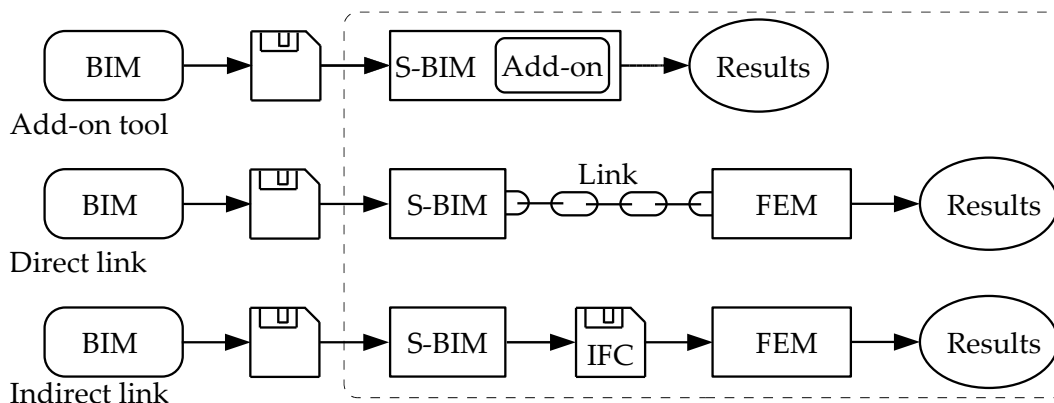
In order to test the applicability of the S-BIM tools in a comprehensive way, structures with various properties are needed. Thus three simple structures with different section properties, geometry, material properties and so on are chosen. The three structures are:

- A simply supported steel beam, presented in Section 3.3. This beam is chosen because it is a very simple structural element in an isotropic material which the S-BIM tools are expected to handle without any errors. The beam is simply supported since this might cause problems regarding the direction of the coordinate system – and consequently the degrees of freedom – by contrast to if the supports were fixed.
- A simply supported timber column, presented in Section 3.4. This structure is chosen to show if the S-BIM tools are able to handle an anisotropic material as timber and to choose the correct design criterion for a column. Furthermore the supports are rotated compared to the steel beam, which the S-BIM tools must be able to handle regardless of different coordinate systems in the applications.
- A continuous concrete beam, presented in Section 3.5. This beam is chosen to show if the S-BIM tools are able to handle a composite material as reinforced concrete and the supports for a continuous beam, since concrete is often used for continuous beams.

The methods used for the tests will be elaborated in the following.

## 3.2 Methods of analysis

The information flow treated in this chapter is illustrated in Figure 3.1.



**Figure 3.1** The information flow from the S-BIM (model) to the results of calculations.

The analyses are performed testing the following S-BIM tools:

- Revit add-on tool (RVT add-on)
- Direct link from Revit to Robot and backwards (RVT ↔ RSA)
- Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)
- Indirect link from Revit to Robot (RVT  $\xrightarrow{\text{IFC}}$  RSA)

As described in Section 2.5 several add-on tools are available for Revit. The add-on tool tested in this chapter is the *Revit Extensions, Simulation - Static Analysis of Frames*.

In order to analyse different structures the S-BIM tools must be able to handle a number of parameters. These parameters are arranged in groups and the applicability of each S-BIM tool is tested step by step. The groups of parameters are:

1. Section properties
2. Geometry
3. Material properties
4. Loads
5. Boundary conditions
6. Design data
7. Results

As described in Section 3.1 three structures have been chosen in order to test the applicability of the S-BIM tools. For each structure initial calculations are made independent of the actual



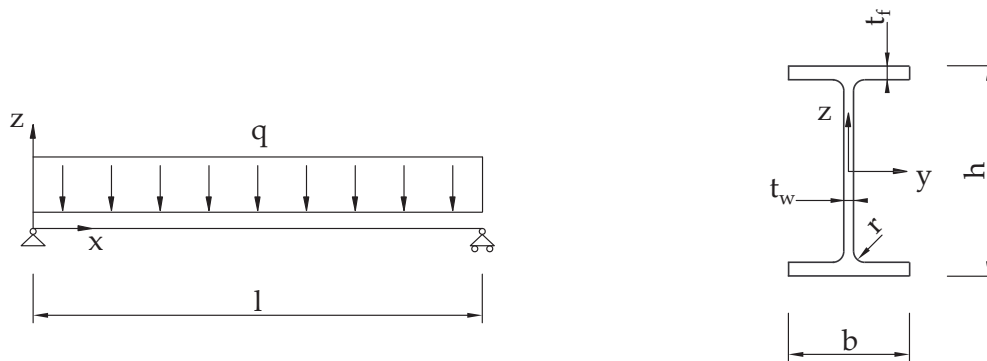
analysis performed. This is done to show which specific parameters in each group of parameters the S-BIM tools must be able to handle in order to make a structural analysis according to Eurocodes.

The calculations are made both by hand and by a suitable software application. StaadPro is used for both the steel and the timber structure, whereas the application *Column and beam design* from NordSoft ApS [Rasmussen and Rasmussen, 2010] is used for the concrete structure. The choice of software applications is not important for the employed method.

### 3.3 Simply supported steel beam

The first structure, for which the tests are performed, is a 6 m simply supported steel beam, subjected to an arbitrary line load of  $q = 5 \text{ kN/m}$  as shown in Figure 3.2. The beam is an IPE200-profile of steel type S235.

The statical system of the steel beam and the cross section are shown in Figure 3.2.



**Figure 3.2** Left: Simply supported beam. Right: Cross section of an IPE profile.

The chosen cross section and magnitude of the line load provides sufficient bending and shear strength but insufficient lateral torsional buckling resistance. This choice is made to ensure that the S-BIM tools not only check the most simple design criteria.

Relevant design criteria for the steel beam are found by a code check cf. BS EN 1993-1-1:2005 [2005] in StaadPro and hand calculations cf. DS/EN 1993-1-1 [2007]. The design criteria are:

- EC3: 6.2.5 Bending moment
- EC3: 6.2.6 Shear
- EC3: 6.3.2 Buckling resistance

The parameters needed to evaluate the three design criteria are presented in Appendix C.1.

No partial factor is applied to the load, since the size of the load is irrelevant in order to evaluate the S-BIM tools and the results obtained. In principle also no partial factors should be applied to the material properties. However partial factors according to BS EN 1993-1-1:2005 [2005] are applied since they are defined by default in both StaadPro and Robot.

In order to test the applicability of updating backwards to Revit changes are made one at a time in Robot and StaadPro, respectively. The tests contain the following changes:

### 3. Analysis of S-BIM tools – simple structures

- The cross section is changed from IPE200 to IPE220
- The length of the beam is changed with 1 m
- The material is changed from steel S235 to S355
- The line load is changed from 5.0 kN/m to 6.0 kN/m
- The supports are changed from pinned and roller to fixed

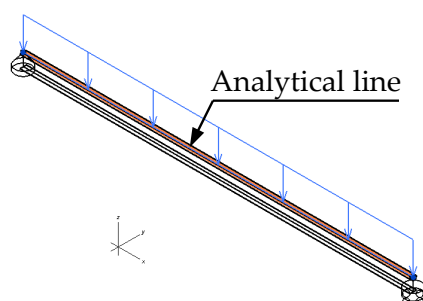
The changes are chosen to show how well the S-BIM tools handle the groups of parameters presented in Section 3.2 when updating backwards to Revit.

#### 3.3.1 Results of tests

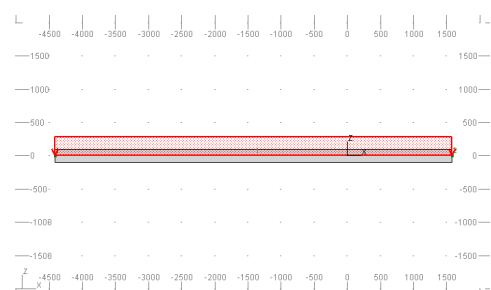
Based on the above described design criteria and the design parameters in Appendix C.1 the applicability of the S-BIM tools are tested by means of the simply supported steel beam. The results are given in Table 3.1 on page 32. Where needed a note is given after the table.

The procedures leading to the results in Table 3.1 demand different choices from the user. The procedures in connection with each S-BIM tool are described in Appendix C.2.

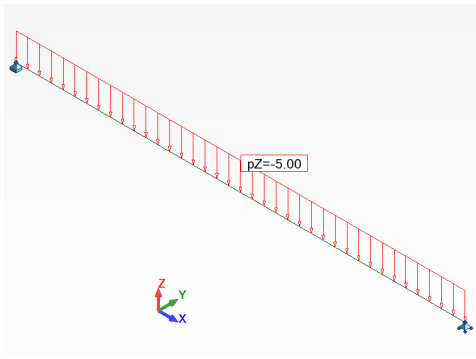
A screendump of the steel beam modelled in Revit is shown in Figure 3.3. After using the add-on tool and the direct links to Robot and StaadPro the steel beam appears as shown in Figure 3.4, 3.5 and 3.6.



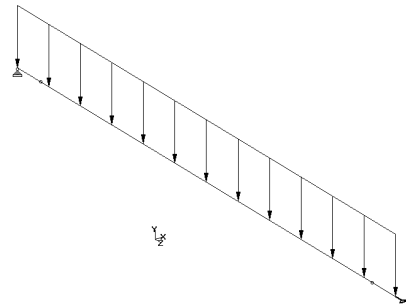
**Figure 3.3** Steel beam with line load in Revit.



**Figure 3.4** Steel beam with line load in the Revit add-on tool.



**Figure 3.5** Steel beam with line load in Robot.



**Figure 3.6** Steel beam with line load in Staad-Pro.

Note that the coordinate system in StaadPro is different from the coordinate systems in Revit and Robot.

As shown in Figure 3.3 the analytical line is placed in the top of the beam which is default in Revit. In Robot and StaadPro the analytical representation of the beam is convergent with the centreline. This difference has no influence of the results for the simply supported beam. However the difference needs to be kept in mind in connection with more complex structures where it can be important.

### 3. Analysis of S-BIM tools – simple structures

|                                   | RVT | RVT<br>add-on | RVT<br>↓<br>RSA | RVT<br>↑<br>RSA | RVT<br>↓<br>SPro | RVT<br>↑<br>SPro | RVT<br>↓ IFC<br>RSA |
|-----------------------------------|-----|---------------|-----------------|-----------------|------------------|------------------|---------------------|
| <b>1. Section properties</b>      |     |               |                 |                 |                  |                  |                     |
| Section class                     | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| Height $h$                        | ✓   | ÷             | ✓               | ✓               | ✓                | ✓                | ÷                   |
| Width $b$                         | ✓   | ÷             | ✓               | ✓               | ✓                | ✓                | ÷                   |
| Web thickness $t_w$               | ✓   | ÷             | ✓               | ✓               | ✓                | ✓                | ÷                   |
| Flange thickness $t_f$            | ✓   | ÷             | ✓               | ✓               | ✓                | ✓                | ÷                   |
| Radius $r$                        | ✓   | ÷             | ÷               | ✓               | ÷                | ✓                | ÷                   |
| Area $A$                          | ✓   | ✓             | ✓               | ✓               | ✓                | ✓                | ÷                   |
| Shear area $A_z$                  | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| Moment of inertia $I_y$           | ÷   | ✓             | ✓               | 1               | ✓                | 1                | ÷                   |
| Moment of inertia $I_z$           | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| Torsion constant $I_t$            | ÷   | ÷             | ÷               | 1               | ÷                | 1                | ÷                   |
| Warping constant $I_w$            | ÷   | ÷             | ÷               | 1               | ÷                | 1                | ÷                   |
| Elastic modulus $W_{el,y}$        | ÷   | ÷             | ÷               | 1               | ✓                | 1                | ÷                   |
| Plastic modulus $W_{pl,y}$        | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| Radius of gyration $i$            | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| <b>2. Geometry</b>                |     |               |                 |                 |                  |                  |                     |
| Length $l$                        | ✓   | ✓             | ✓               | ÷               | ✓                | ÷                | ✓                   |
| Effective length $l_{eff}$        | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| <b>3. Material properties</b>     |     |               |                 |                 |                  |                  |                     |
| Yield stress $f_y$                | ✓   | ÷             | ✓               | ÷               | ÷ <sup>2</sup>   | ÷                | ÷                   |
| Modulus of elasticity $E$         | ✓   | ✓             | ✓               | ÷               | ✓                | ÷                | ÷                   |
| Shear modulus $G$                 | ✓   | ÷             | ✓               | ÷               | ✓                | ÷                | ÷                   |
| Density $\rho$                    | ✓   | ✓             | ✓               | ÷               | ✓                | ÷                | ÷                   |
| <b>4. Loads</b>                   |     |               |                 |                 |                  |                  |                     |
| Magnitude $q$                     | ✓   | ✓             | ✓               | ÷               | ✓                | ÷                | ÷ <sup>3</sup>      |
| Position                          | ✓   | ✓             | ✓               | ÷               | ✓                | ÷                | ÷ <sup>3</sup>      |
| <b>5. Boundary conditions</b>     |     |               |                 |                 |                  |                  |                     |
| Pinned                            | ✓   | ✓             | ✓               | ÷               | ✓                | ÷                | ÷ <sup>3</sup>      |
| Roller                            | ✓   | ✓             | ✓               | ÷               | ÷ <sup>4</sup>   | ÷                | ÷ <sup>3</sup>      |
| <b>6. Design data</b>             |     |               |                 |                 |                  |                  |                     |
| Moment capacity $M_{c,R}$         | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| Shear capacity $V_{c,R}$          | ÷   | ÷             | ÷               | 1               | ✓                | 1                | ÷                   |
| Reduction factor $\chi_{LT}$      | ÷   | ÷             | ✓ <sup>5</sup>  | 1               | ÷                | 1                | ÷                   |
| Imperfection factor $\alpha_{LT}$ | ÷   | ÷             | ✓ <sup>5</sup>  | 1               | ÷                | 1                | ÷                   |
| Buckling curve                    | ÷   | ÷             | ✓ <sup>5</sup>  | 1               | ÷                | 1                | ÷                   |
| LTB moment capacity $M_{b,R}$     | ÷   | ÷             | ✓ <sup>5</sup>  | 1               | ✓                | 1                | ÷                   |
| <b>7. Results</b>                 |     |               |                 |                 |                  |                  |                     |
| Deflection                        | ÷   | ✓             | ✓ <sup>6</sup>  | 1               | ✓                | 1                | ÷                   |
| Section forces                    | ÷   | ✓             | ✓               | 1               | ✓                | 1                | ÷                   |
| EC3 6.2.5                         | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |
| EC3 6.2.6 (Z)                     | ÷   | ÷             | ÷               | 1               | ✓                | 1                | ÷                   |
| EC3 6.3.2 LTB                     | ÷   | ÷             | ✓               | 1               | ✓                | 1                | ÷                   |

**Table 3.1** Test results for the simply supported steel beam. ✓ means no problems and ÷ means that it does not work or that the parameter/feature is not available.

Notes to Table 3.1:

- 1) This parameter is not available in Revit.
- 2) By default set to 235 MPa in StaadPro. Must be defined manually if different from this value.
- 3) Due to the limitations of the IFC Coordination View, cf. Section 2.5.3.
- 4) The degrees of freedom should be  $fx\text{ffff}^+$  in Revit coordinates corresponding to  $xx\text{ffff}$  in StaadPro coordinates but the degrees of freedom are  $ffx\text{fff}$  in StaadPro coordinates.
- 5) In Robot the lateral torsional buckling curve is set to “b”, but should have been “a”. Thus the imperfection factor and reduction factor and thereby the lateral torsional buckling moment capacity are different from the hand calculations. Furthermore the critical moment for lateral-torsional buckling is calculated accordingly to another theory (ENV311) than used in the hand calculations and StaadPro.
- 6) The deflection is 18 mm without code check, but 22 mm at code check. The correct result is 22 mm cf. Table C.7 in Appendix C.1

### 3.3.2 Evaluation of tests

Based on the results presented in Table 3.1 an evaluation of the tests performed for the steel beam is made.

#### Revit add-on tool (RVT add-on)

★ ☆ ☆ ☆ ☆

In the first test the Revit add-on tool *Revit Extensions, Simulation - Static Analysis of Frames* gets one star because it is useful in relation to compute the section forces and deflection. On the other hand it is not possible to assess the design criteria with the Revit add-on tool.

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

★ ★ ★ ★ ☆

The direct link from Revit to Robot and backwards gets four stars because it is possible to exchange all relevant data from Revit to Robot. However, only the section properties are updated backwards from Robot to Revit. Note that a code check in Robot does not include shear, however this has nothing to do with the link and therefore does not influence the evaluation.

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

★ ★ ★ ★ ☆

Like the link between Revit and Robot the direct link from Revit to StaadPro and backwards gets four stars. All the relevant parameters are exchanged from Revit to StaadPro which makes the link useful as a one way link. However, only the section properties are updated backwards from StaadPro to Revit.

#### Indirect link from Revit to Robot (RVT $\xrightarrow{\text{IFC}}$ RSA)

☆ ☆ ☆ ☆ ☆

The last test with the steel beam is performed with an indirect link from Revit to Robot. The IFC-link gets zero stars because only the length of the steel beam was exchanged from Revit to

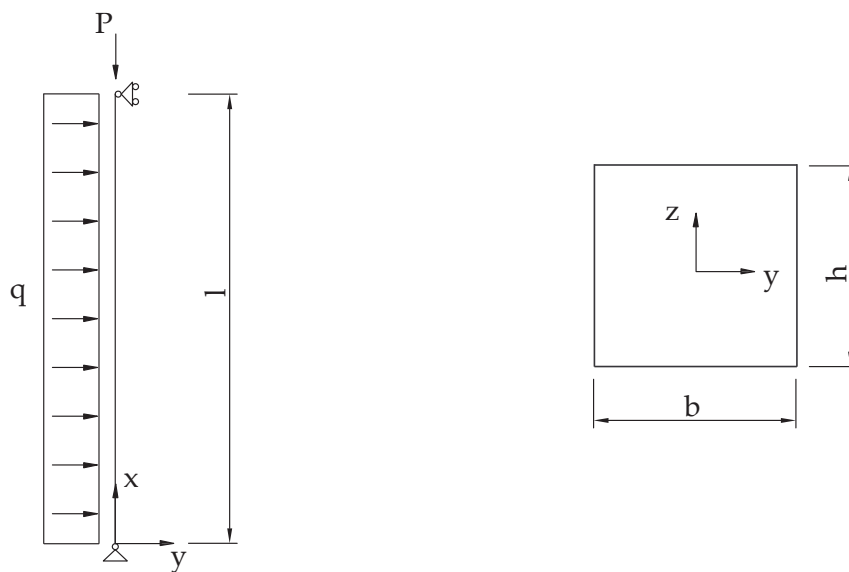
<sup>†</sup> $f$  marks a free degree of freedom whereas  $x$  marks a fixed degree of freedom. The three first positions are related to the translations in the three directions (x, y and z) and the three last positions are related to the rotations about the three directions.

Robot. Thus the only optimisation in connection with the IFC-link is that it is possible to reuse node and bar coordinates.

#### 3.4 Simply supported timber column

The second structure, for which the tests are performed, is a 3 m simply supported timber column, subjected to an arbitrary point load of  $P = 20$  kN and a line load of  $q = 5$  kN/m as shown in Figure 3.7. The point load is a permanent load and the line load is an instantaneous load. The column is  $150 \times 150$  mm and made of timber C24.

The statical system of the timber column and the cross section are shown in Figure 3.7.



**Figure 3.7** Left: Simply supported column. Right: Cross section.

A relevant design criterion for the timber column is found by StaadPro and hand calculations cf. DS/EN 1995-1-1 [2007]. The design criterion is:

- EC5: 6.3.2 Columns subjected to combined compression and bending

The parameters needed to evaluate the design criterion are presented in Appendix D.1.

As it was the case for the steel beam, no partial factors are applied to the loads. Partial factors are applied to the material properties cf. DS/EN 1995-1-1 [2007], since they are defined by default in both StaadPro and Robot.

In order to test the applicability of updating backwards to Revit the following changes are made:

- The cross section is changed from  $150 \times 150$  mm to  $125 \times 125$  mm
- The length of the column is changed from 3.0 m to 3.2 m
- The material is changed from timber C24 to Gl32c
- The line load is changed from 5.0 kN/m to 6.0 kN/m

- The supports are changed from pinned and roller to fixed

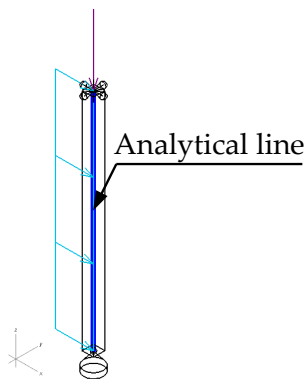
The changes are chosen to show how well the S-BIM tools handle the groups of parameters presented in Section 3.2 when updating backwards to Revit from Robot and StaadPro, respectively.

#### 3.4.1 Results of tests

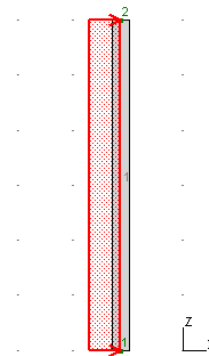
Based on the design criterion described above and the design parameters in Appendix D.1 the applicability of the S-BIM tools are tested by means of the simply supported timber column. The results are given in Table 3.2 on the next page.

The procedures leading to the results in Table 3.2 demand different choices from the user. The procedures in connection with each S-BIM tool are described in Appendix D.2.

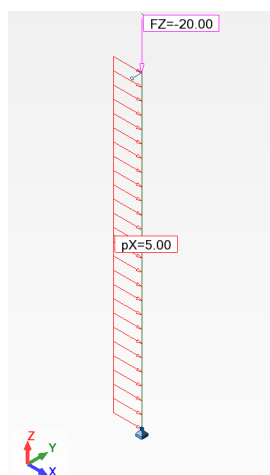
A screendump of the timber column modelled in Revit is shown in Figure 3.8. After using the add-on tool and the direct links to Robot and StaadPro the timber column appears as shown in Figure 3.9, 3.10 and 3.11.



**Figure 3.8** Timber column with loads in Revit.



**Figure 3.9** Timber column with line load in the Revit add-on tool.



**Figure 3.10** Timber column with loads in Robot.



**Figure 3.11** Timber column with loads in StaadPro.

### 3. Analysis of S-BIM tools – simple structures

Note that in both the Revit add-on tool, Robot and StaadPro the anisotropic timber is treated as isotropic.

The analytical line for the column is placed in the centre by default in Revit. This corresponds with the analytical representation of the column in Robot and StaadPro.

|   | RVT | RVT<br>add-on  | RVT<br>↓<br>RSA | RVT<br>↑<br>RSA | RVT<br>↓<br>SPro | RVT<br>↑<br>SPro | RVT<br>↓ IFC<br>RSA |
|---|-----|----------------|-----------------|-----------------|------------------|------------------|---------------------|
| <b>1. Section properties</b>                    |     |                |                 |                 |                  |                  |                     |
| Height $h$                                      | ✓   | ÷              | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                | ✓                   |
| Width $b$                                       | ✓   | ÷              | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                | ✓                   |
| Area $A$  | ✓   | ✓              | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                | ✓                   |
| Moment of inertia $I_y$                         | ✓   | ✓              | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                | ✓                   |
| Elastic modulus $W_{el,y}$                      | ✓   | ÷              | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                | ÷                   |
| <b>2. Geometry</b>                              |     |                |                 |                 |                  |                  |                     |
| Length $l$                                      | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ✓                   |
| <b>3. Material properties</b>                   |     |                |                 |                 |                  |                  |                     |
| Characteristic bending strength $f_{m,k}$       | ✓   | ÷              | ✓               | ÷               | ÷                | ÷                | ÷                   |
| Characteristic compressive strength $f_{c,0,k}$ | ✓   | ÷              | ✓               | ÷               | ÷                | ÷                | ÷                   |
| Characteristic modulus of elasticity $E_k$      | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ÷                   |
| Density $\rho$                                  | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ÷                   |
| <b>4. Loads</b>                                 |     |                |                 |                 |                  |                  |                     |
| Duration  | ÷   | ÷              | ✓ <sup>3</sup>  | 1               | ✓ <sup>3</sup>   | 1                | ÷ <sup>4</sup>      |
| Magnitude $P, q$                                | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ÷ <sup>4</sup>      |
| Position  | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ÷ <sup>4</sup>      |
| Combination                                     | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ÷ <sup>4</sup>      |
| <b>5. Boundary conditions</b>                   |     |                |                 |                 |                  |                  |                     |
| Pinned  | ✓   | ✓              | ✓               | ÷               | ✓                | ÷                | ÷ <sup>4</sup>      |
| Roller  | ✓   | ✓              | ✓               | ÷               | ÷ <sup>5</sup>   | ÷                | ÷ <sup>4</sup>      |
| <b>6. Design data</b>                           |     |                |                 |                 |                  |                  |                     |
| Allowable bending stress $f_{m,d}$              | ÷   | ÷              | ✓               | 1               | ÷                | 1                | ÷                   |
| Allowable normal stress $f_{c,d}$               | ÷   | ÷              | ✓               | 1               | ÷                | 1                | ÷                   |
| Modification factor $k_{mod}$                   | ÷   | ÷              | ✓               | 1               | ÷                | 1                | ÷                   |
| Instability factor $k_c$                        | ÷   | ÷              | ✓               | 1               | ÷                | 1                | ÷                   |
| Service class                                   | ÷   | ÷              | ✓               | 1               | ÷                | 1                | ÷                   |
| <b>7. Results</b>                               |     |                |                 |                 |                  |                  |                     |
| Section forces                                  | ÷   | ÷ <sup>6</sup> | ✓               | 1               | ÷                | 1                | ÷                   |
| EC5: 6.3.2                                      | ÷   | ÷              | ✓               | 1               | ÷                | 1                | ÷                   |

**Table 3.2** Test results for the simply supported timber column. ✓ means no problems and ÷ means that it does not work or that the parameter/feature is not available.

Notes to Table 3.2:

- 1) This parameter is not available in Revit.
- 2) When changing the cross section in Robot the column is stored in a wrong family\* in Revit.

\*Families in Revit are classes of elements. A family groups elements with a common set of parameters or properties, identical use, and similar graphical representation [Revit Metric Tutorials, 2009].



If the new cross section already exists in Revit the application will choose the right family.

- 3) Load duration is not available in Revit and must be added manually before analyses are performed.
- 4) Due to the limitations of the IFC Coordination View, cf. Section 2.5.3.
- 5) The degrees of freedom should be  $xxffff$  in Revit coordinates corresponding to  $xfxfff$  in StaadPro coordinates but the degrees of freedom are  $xxffff$  in StaadPro coordinates.
- 6) The directions are changed so that vertical is horizontal i.e. the reactions and section forces are wrong.

### 3.4.2 Evaluation of tests

Based on the results presented in Table 3.2 an evaluation of the applicability of the S-BIM tools in relation to the timber column is made.

#### Revit add-on tool (RVT add-on)

☆☆☆☆

The add-on tool *Revit Extensions, Simulation - Static Analysis of Frames* gets no stars because it is not possible to compute neither the deflection nor the section forces, or to assess the design criteria.

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

★★★☆☆

The link gets three stars because it is possible to exchange all relevant data from Revit to Robot. However Revit can only update the cross section if the cross section was preloaded in Revit.

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

★★☆☆☆

The link gets two stars because it is useful in relation to geometry, material properties, loads and partly supports, whereas the cross section must be defined manually. If this is done StaadPro checks the same design criterion as Robot and gives the same results. The link from StaadPro to Revit is useless since no information can be exchanged this way.

#### Indirect link from Revit to Robot (RVT $\xrightarrow{\text{IFC}}$ RSA)

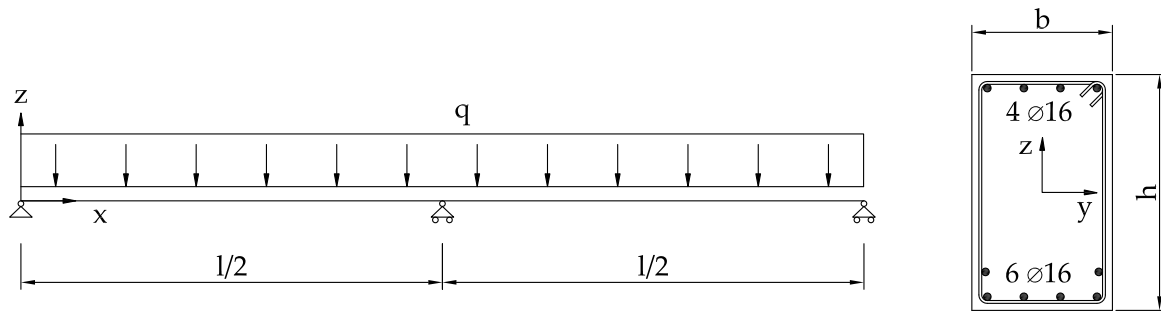
☆☆☆☆

The IFC-link also gets zero stars in this test because only the length and the cross section of the timber column was exchanged from Revit to Robot.

## 3.5 Continuous concrete beam

The third structure, for which the tests are performed, is a continuous concrete beam with two spans of 6.3 m. The beam is subjected to an arbitrary line load of  $q = 50 \text{ kN/m}$  as shown in Figure 3.12. The beam is  $300 \times 500 \text{ mm}$  and the concrete is C25/30. In the bottom of the beam 6  $\varnothing 16 \text{ mm}$  reinforcement bars are placed and in the top of the beam 4  $\varnothing 16 \text{ mm}$  reinforcements bars are placed. Furthermore  $\varnothing 6 \text{ mm}$  stirrups with varying spacing are placed according to the variation of the shear force.

The statical system of the concrete beam and the cross section are shown in Figure 3.12.



**Figure 3.12** Left: Continuous beam. Right: Cross section.

There are many design possibilities with different levels of detail for reinforced concrete. The design criteria for the reinforced concrete beam in these tests are based on a calculation in the application *Column and beam design* from NordSoft ApS and a simple hand calculation, where the section forces are calculated by means of plasticity. The chosen design criteria are:

- The amount of reinforcement should fulfil  $\omega_{min} \leq \omega \leq \omega_{bal}$
- The moment capacity must be larger than the acting moment,  $M_R \geq M$
- The inclined concrete compressive stress must be less than the plastic strength,  

$$\sigma_c = \tau_{Ed} (\tan \theta + \cot \theta) \leq \nu_v f_{cd}$$

The parameters needed to evaluate the three design criteria are presented in Appendix E.1.

Since it is not clear whether the S-BIM tools use plasticity or elasticity, an elastic design of the reinforced concrete beam is performed with the application *Column and beam design* from NordSoft ApS.

As for the previous structures, no partial factors are applied to the load, since the size of the load is irrelevant in order to evaluate the S-BIM tools and the results obtained. Partial factors are applied to the materials cf. DS/EN 1992-1-1 [2008], since they are defined by default in both StaadPro and Robot.

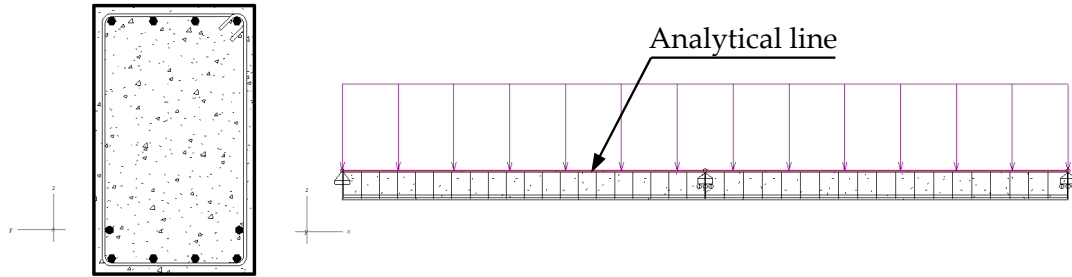
#### 3.5.1 Results of tests

Based on the design criteria described above and the design parameters in Appendix E.1 the applicability of the S-BIM tools are tested by means of the continuous concrete beam. The results are given in Table 3.3 on page 40.

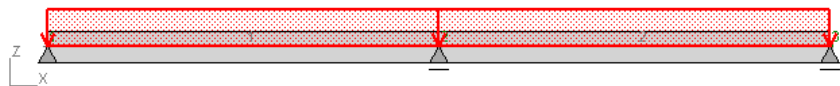
The procedures leading to the results in Table 3.3 demand different choices from the user. The procedures in connection with each S-BIM tool are described in Appendix E.2.

In the tests performed for the concrete beam, the updating backwards to Revit from Robot or StaadPro has not been performed. The reason for this is that the results of the exchange from Revit to the two applications are rather incomplete, since the reinforcement modelled in Revit is not transferred to neither Robot nor StaadPro. Therefore it is not relevant to update the models back to Revit. Alternative possibilities for modelling reinforced concrete in the S-BIM tools are described in Section 3.5.3.

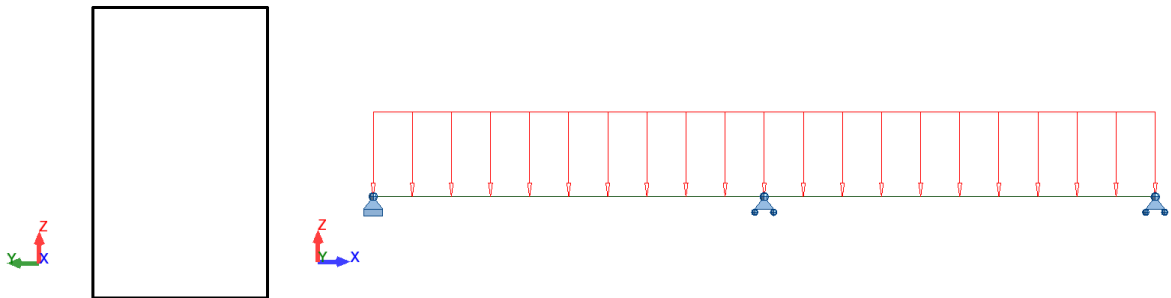
A screendump of the concrete beam modelled in Revit is shown in Figure 3.13. After using the add-on tool and the direct links to Robot and StaadPro the concrete beam appears as shown in Figure 3.14, 3.15 and 3.16.



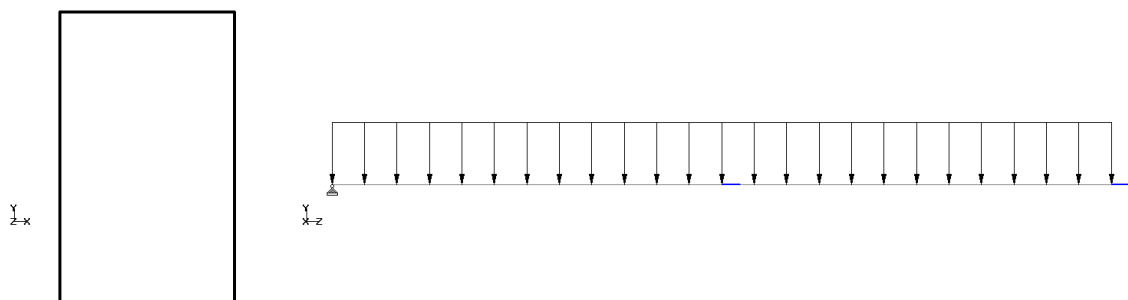
**Figure 3.13** Left: Cross section of reinforced concrete beam in Revit. Right: Reinforced concrete beam with line load in Revit.



**Figure 3.14** Concrete beam with line load in the Revit add-on tool. The cross section is not available.



**Figure 3.15** Left: Cross section of concrete beam in Robot. Right: Concrete beam with line load in Robot.



**Figure 3.16** Left: Cross section of concrete beam in StaadPro. Right: Concrete beam with line load in StaadPro.

As previously described and shown in Figure 3.13 to 3.16 the analytical line is placed in the top of the beam in Revit but in the centre of the beam in Robot and StaadPro. This difference still does not influence the results.

### 3. Analysis of S-BIM tools – simple structures

|   | RVT | RVT<br>add-on  | RVT<br>↓<br>RSA | RVT<br>↓<br>SPro | RVT<br>↓ IFC<br>RSA |
|---|-----|----------------|-----------------|------------------|---------------------|
| <b>1. Section properties</b>                    |     |                |                 |                  |                     |
| Height $h$                                      | ✓   | ÷              | ✓               | ✓                | ✓                   |
| Width $b$                                       | ✓   | ÷              | ✓               | ✓                | ✓                   |
| Moment of inertia $I_y$                         | ÷   | ✓              | ✓               | ÷                | ✓                   |
| Effective height $d$                            | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Internal moment arm $z$                         | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Diameter of reinforcement                       | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Number of reinforcement                         | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Diameter of stirrups                            | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Spacing of stirrups $s$                         | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Position of reinforcement $c_{s1}, c_{s2}, c_s$ | ✓   | ÷              | ÷               | ÷                | ÷                   |
| <b>2. Geometry</b>                              |     |                |                 |                  |                     |
| Length  | ✓   | ✓              | ✓               | ✓                | ✓                   |
| <b>3. Material properties</b>                   |     |                |                 |                  |                     |
| Yield strength of reinforcement $f_{yk}$        | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Modulus of elasticity $E_s$                     | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Strength of concrete $f_{ck}$                   | ✓   | ÷              | ÷               | ÷                | ÷                   |
| Axial tensile strength of concrete $f_{ctm}$    | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Modulus of elasticity $E$                       | ✓   | ✓              | ÷               | ✓                | ÷                   |
| Density   | ✓   | ✓              | ÷               | ✓                | ÷                   |
| Ultimate compressive strain $\varepsilon_{cu3}$ | ÷   | ÷              | ÷               | ÷                | ÷                   |
| <b>4. Loads</b>                                 |     |                |                 |                  |                     |
| Duration  | ÷   | ÷              | ÷               | ÷                | ÷ <sup>1</sup>      |
| Magnitude $q$                                   | ✓   | ✓              | ✓               | ✓                | ÷ <sup>1</sup>      |
| Position  | ✓   | ✓              | ✓               | ✓                | ÷ <sup>1</sup>      |
| Combination                                     | ✓   | ✓              | ✓               | ✓                | ÷ <sup>1</sup>      |
| <b>5. Boundary conditions</b>                   |     |                |                 |                  |                     |
| Pinned  | ✓   | ✓              | ✓               | ✓                | ÷ <sup>1</sup>      |
| Roller  | ✓   | ✓              | ✓               | ÷ <sup>2</sup>   | ÷ <sup>1</sup>      |
| <b>6. Design data</b>                           |     |                |                 |                  |                     |
| Control class                                   | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Environmental class                             | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Maximum aggregate size                          | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Moment capacity                                 | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Factor $\lambda$                                | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Reinforcement degree $\omega_{bal}$             | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Reinforcement degree $\omega_{min}$             | ÷   | ÷              | ÷               | ÷                | ÷                   |
| Actual $\omega$                                 | ÷   | ÷              | ÷               | ÷                | ÷                   |
| <b>7. Results</b>                               |     |                |                 |                  |                     |
| Deflection                                      | ÷   | ✓              | ✓               | ✓                | ÷                   |
| Section forces                                  | ÷   | ✓ <sup>3</sup> | ✓ <sup>3</sup>  | ✓ <sup>3</sup>   | ÷                   |
| $\omega_{min} \leq \omega \leq \omega_{bal}$    | ÷   | ÷              | ÷               | ÷                | ÷                   |
| $M_R \geq M$                                    | ÷   | ÷              | ÷               | ÷                | ÷                   |
| $\sigma_c \leq \nu_v f_{cd}$                    | ÷   | ÷              | ÷               | ÷                | ÷                   |

**Table 3.3** Test results for the continuous concrete beam. ✓ means no problems and ÷ means that it does not work or that the parameter/feature is not available.

Notes to Table 3.3:

- 1) Due to the limitations of the IFC Coordination View, cf. Section 2.5.3.
- 2) The degrees of freedom should be *fixfff* in Revit coordinates corresponding to *xxffff* in StaadPro coordinates but the degrees of freedom are *ffxffff* in StaadPro coordinates.
- 3) Elastic calculation (Hand calculation: Plastic).

### 3.5.2 Evaluation of tests

Based on the results presented in Table 3.3 an evaluation of the applicability of the S-BIM tools in relation to the continuous concrete beam is made.

#### Revit add-on tool (RVT add-on)

★ ☆ ☆ ☆ ☆

The add-on tool *Revit Extensions, Simulation - Static Analysis of Frames* gets one star since the extension is useful in relation to compute the deflection and elastic section forces, but useless in relation to assess the design criteria. However in this test the extension is as good as the direct links.

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

★ ☆ ☆ ☆ ☆

The link from Revit to Robot gets one star in the performed test because the results are identical to the results obtained with the Revit Extension.

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

★ ☆ ☆ ☆ ☆

The link from Revit to StaadPro also gets one star in the performed test because the results are identical to the results obtained with the Revit Extension and the link between Revit and Robot.

#### Indirect link from Revit to Robot (RVT $\xrightarrow{\text{IFC}}$ RSA)

☆ ☆ ☆ ☆ ☆

The IFC-link gets zero stars because only the length and the cross section of the continuous concrete beam were exchanged from Revit to Robot.

### 3.5.3 Alternative procedures

Since the previous tests of designing concrete structures were not very successful some alternatives are presented. In stead of modelling the concrete and the reinforcement in Revit and then exchanging both to the calculation software, only the concrete is modelled in Revit. Hence the calculation software is used to find the necessary amount of reinforcement. Three different alternatives are presented briefly in the following.

#### Revit Extensions, Reinforcement Design

This tool is used to utilize *RC Beams* in Robot which is used to calculate the necessary amount and placement of reinforcement according to EN 1992-1-1:2004 AC:2008 [2004]. The result is that 8  $\varnothing 16$  mm reinforcement bars are needed in the top of the beam and 10  $\varnothing 16$  mm reinforcement bars are needed in the bottom as shown in Figure 3.17. This is fairly different from the result of the hand calculations. This might be due to the fact that Robot is based on elastic calculations where the hand calculations are based on plasticity. Note that the yield strength of the reinforcement is not 550 MPa but 500 MPa.

It is possible to update the reinforcement calculated in Robot back to Revit.

### 3. Analysis of S-BIM tools – simple structures

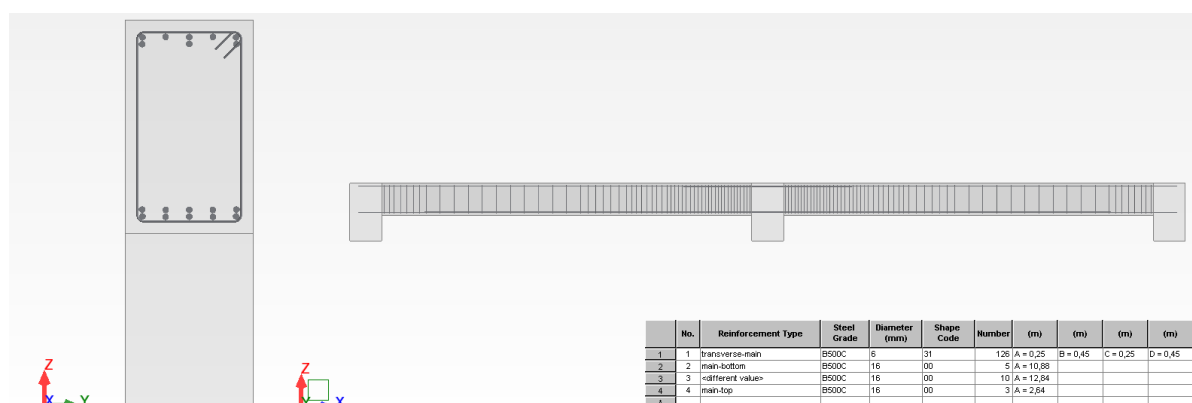


Figure 3.17 Screenshot from Robot RC Beams.

#### Revit Extensions, Integration with Robot Structural Analysis

This tool is used to utilize Robot where *Structure design, RC Members - required reinf.* is used to calculate the necessary amount of reinforcement according to EN 1992-1-1:2004 AC:2008 [2004]. The result is that 7  $\varnothing 16$  mm reinforcement bars are needed in the top of the beam and 3  $\varnothing 16$  mm reinforcement bars are needed in the bottom, as shown in Figure 3.18. This is fairly different from the result of the hand calculations and the result obtained by use of *RC Beams*. No specific information about the placement of the reinforcement is given.

It is not possible to update the structure in Revit.

| Required Member Reinforcement |                                       |                                       |  |  |                      |                               |                        |   |
|-------------------------------|---------------------------------------|---------------------------------------|--|--|----------------------|-------------------------------|------------------------|---|
| Bar/Position (m)              | Top required reinforcement (My) (cm2) | Top reinforcement - distribution (My) | Bottom required reinforcement (My) (cm2) | Bottom reinforcement - distribution (My) | Stirrup spacing (cm) | Provided stirrup spacing (cm) | Design moment My (kNm) | Transversal reinforcement - type/distribution |
| 1/ 6,30                       | 13,81                                 | 7116                                  | 0,0                                      | -  | 5,4                  | 4,0                           | -264,81                |   |
| 1/ 0,40                       | 0,0                                   | -                                     | 2,41                                     | 2f16                                     | 10,8                 | 8,0                           | 46,52                  |   |
| 1/ 9,25                       | 0,0                                   | -                                     | 5,93                                     | 3f16                                     | 25,9                 | 8,0                           | 124,39                 |   |
| 1/ 12,20                      | 0,0                                   | -                                     | 2,41                                     | 2f16                                     | 10,8                 | 8,0                           | 46,52                  |   |
| 1/ 3,35                       | 0,0                                   | -                                     | 5,93                                     | 3f16                                     | 25,9                 | 8,0                           | 124,39                 |   |
| 1                             |                                       |                                       |  |  |                      |                               |                        | 2f16 52*8.0+105*4.0+52*8.0                    |

Figure 3.18 Screenshot from Robot Structure design, RC Members - required reinf.

#### SI Xchange

This tool is used to utilize StaadPro where *Design - Concrete: EC2* can be used to calculate the necessary amount of reinforcement according to Eurocode 2. The result is that 8  $\varnothing 16$  mm reinforcement bars are needed in the top of the beam and 4  $\varnothing 16$  mm reinforcement bars are needed in the bottom as shown in Figure 3.19. This is also fairly different from the result of the hand calculations and the result obtained by use of *RC Beams* and *Structure design, RC Members - required reinf.*

It is not possible to update the structure in Revit.

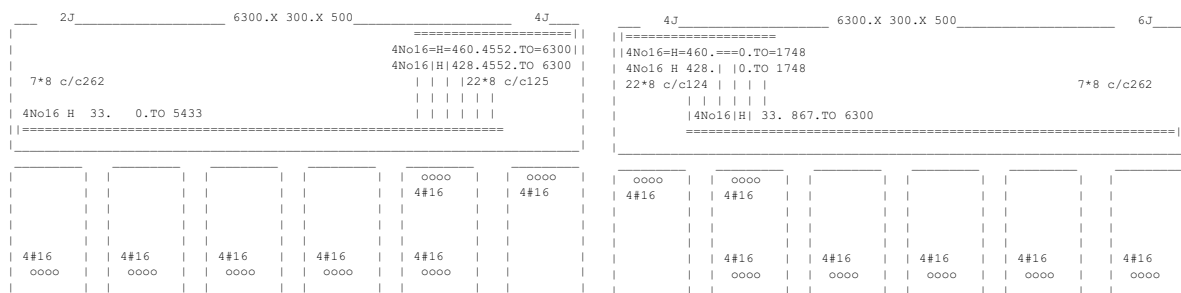


Figure 3.19 Output from StaadPro, Design - Concrete: EC:2.

The outputs from the three alternatives are rather different, both from each other and from the hand calculations. Thus it is difficult to recommend one of the methods, but in relation to this study *Revit Extensions, Reinforcement Design* is most preferable since it is possible to export the concrete structure without reinforcement from Revit, then calculate/model the reinforcement in Robot, and finally send the reinforcement back to Revit.

### 3.6 Subconclusion

In order to give an initial answer to the thesis statement, presented in Section 2.6, this chapter has been divided in three sections where different simple structures have formed the basis of this evaluation of the applicabilities of the tested S-BIM tools.

In Section 3.3 a simply supported steel beam was chosen since it is a very simple structural element in an isotropic material which the S-BIM tools were expected to handle without any errors.

In Section 3.4 a simply supported timber column was chosen to show if the S-BIM tools were able to handle an anisotropic material as timber. Furthermore the supports were rotated compared to the beam, which the S-BIM tools should be able to handle regardless of different default coordinate systems in the applications.

In Section 3.5 a continuous concrete beam was chosen to show if the S-BIM tools were able to handle a composite material as reinforced concrete and the supports for a continuous beam.

For both the steel beam and the reinforced concrete beam the analytical line was placed in the top of the beam by default in Revit. By contrast the analytical representation of the beam is convergent with the centreline in Robot and StaadPro. This difference have no influence of the results for these simple structures. However the difference needs to be kept in mind in connection with the more complex structures in the following chapters.

#### Revit add-on tool (RVT add-on)

When analysing both the simply supported steel beam and the continuous concrete beam it is concluded that the add-on tool *Revit Extensions, Simulation - Static Analysis of Frames* is capable of calculating section forces and deflection. This can give an overview of the structure in a feasibility study. No useful results could be found by use of the Revit add-on tool when testing the timber column. No assessment of the design criteria given in the Eurocodes is possible in the employed add-on tool.

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

This direct link *Integration with Robot Structural Analysis* makes it possible to evaluate the steel

structure according to Eurocode 3, and full one-way linking from Revit to Robot is possible. Only the section properties are updated backwards from Robot to Revit. The timber structure is evaluated according to Eurocode 5, and almost full one-way linking is possible. The cross section can be updated if a library of the necessary families is created in Revit. It has not been possible to transfer the reinforcement modelled in Revit to Robot, hence the results from the analysis made in Robot are similar to those obtained by the Revit add-on tool in connection with the concrete beam.

#### **Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)**

The results of the tests of the direct link *SI Xchange* are quite similar to those for the direct link from Revit to Robot and backwards, except for the fact that this direct link does not support timber materials cf. Section 2.5.2. The fact that it is only possible to update section properties backwards to Revit, is in compliance with Section 2.5.2, where it is stated that only the size changes and column rotations are being updated in Revit.

#### **Indirect link from Revit to Robot (RVT $\xrightarrow{\text{IFC}}$ RSA)**

The indirect IFC-link is rather useless in the tests performed in this chapter, since primarily node and bar coordinates are transferred. This is not due to limitations of the IFC file format but due to limitations in the implementation of IFC in Revit and Robot, where only IFC 2x3 Coordination View is supported. In complex structures the IFC-link might be to the of benefit of the workflow regardless of the limitations.

Even though the structures in the following chapters are more complex, the IFC-file format will not be tested further due to the limitations of the implementation of IFC in Revit and Robot.

Based on the tests performed in this chapter it is concluded that the link *Integration with Robot Structural Analysis* is most preferable.

Both direct links fulfilled the expectations in connection with the steel beam in an equal manner.

Regarding the expectations in connection with the timber column none of the S-BIM tools were able to handle the timber as an anisotropic material. Still the link *Integration with Robot Structural Analysis* is considered best, since it is the only link which could handle the rotated supports and the cross section of the timber column.

Regarding the concrete beam it is concluded that none of the S-BIM tools were able to handle the composite material, since it is not possible to transfer reinforcement from Revit to any of the calculation software tested. Though, it is possible to model the reinforcement in Robot and then transfer it back to Revit, which might be the most preferable workflow in practice.

Based on this evaluation reinforced concrete will not be treated further in this project. Tests based on a timber structure and a steel structure, with an increasing degree of complexity, will be described in the next two chapters.

The timber frame structure in Chapter 4 is chosen regardless of the limitations of the *SI Xchange* link in connection with timber. The reason for this is that it still might be an optimisation of the information flow, since it is possible to transfer the geometry, loads and supports with the link, and it is rather easy to assign the section properties and material properties manually in StaadPro.



## Analysis of S-BIM tools – timber frame structure

---

In this chapter, three of the S-BIM tools, presented in Section 2.6, are analysed through a timber frame structure. Following an evaluation of the S-BIM tools are given.

---

### 4.1 Introduction

In this chapter the applicability of each S-BIM tool is tested with a timber frame structure from Krafthallen which is a sports centre in Tromsø, Norway. Krafthallen is shown in Figure 4.1. The sports centre consists of 14 timber frames as the main structural elements. Krafthallen was built in 1999 and severe shear cracks in three of the 14 timber frames were detected in March 2003. An analysis of damages to the structure and a description of the structure are given in Bell [2005].



**Figure 4.1** Krafthallen in Tromsø [Bell, 2005, p. 1].

One of the timber frame structures is shown in Figure 4.2. The timber frame structure is chosen to see if the S-BIM tools can handle a structure which is more advanced than the simple structures in Chapter 3. The structure is more advanced in the sense that several elements are joint together, that neither of the elements are vertical nor horizontal, and that several of the beams are tapered with varying section height.

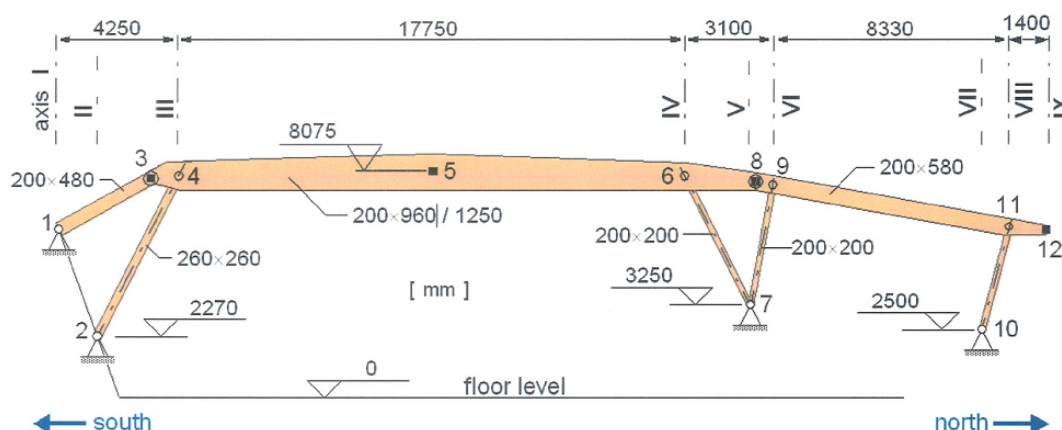


Figure 4.2 Timber frame structure [Kirkegaard and Sørensen, 2008, p. 7].

### 4.2 Methods of analysis

The specific method used in this chapter corresponds with the method used in Chapter 3 except that the indirect link is no longer treated since the simple tests showed that the benefit of using IFC was relative low with the employed applications. Thus the information flow treated appears as illustrated in Figure 4.3.

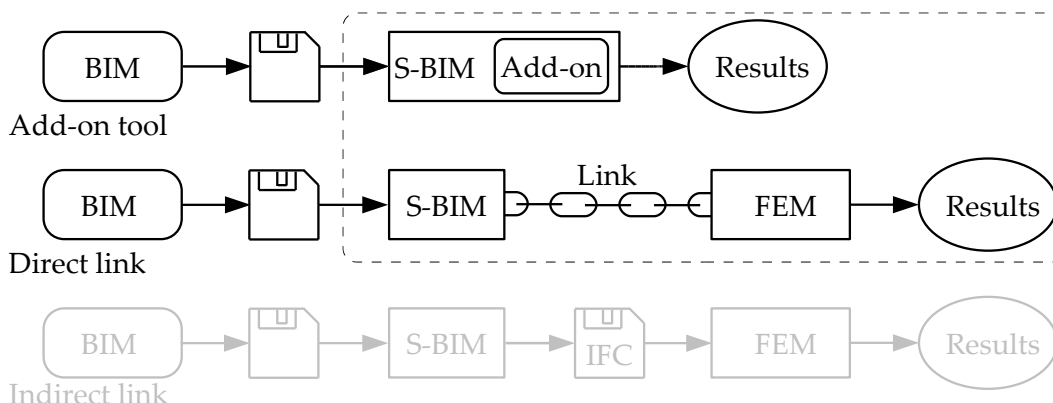


Figure 4.3 The information flow from the S-BIM (model) to the results of calculations.

The following S-BIM tools are tested:

- Revit add-on tool (RVT add-on)
- Direct link from Revit to Robot and backwards (RVT ↔ RSA)
- Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

Again the Revit add-on tool tested is the *Revit Extensions, Simulation - Static Analysis of Frames*.

The parameters which the S-BIM tools must be able to handle are arranged in the same groups as described in Chapter 3. These groups of parameters are still:

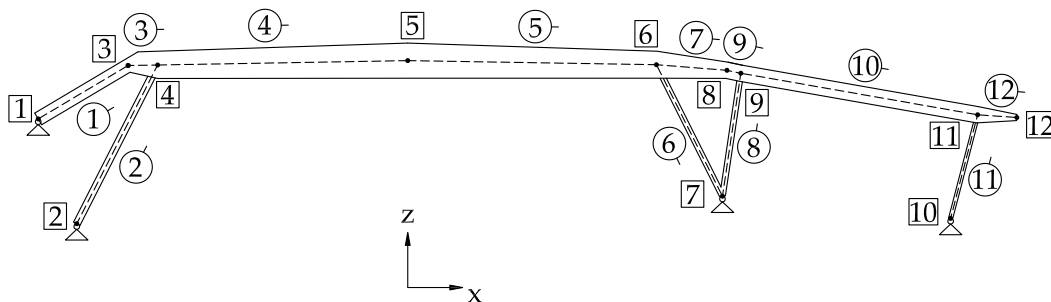
1. Section properties
2. Geometry
3. Material properties
4. Loads
5. Boundary conditions
6. Design data
7. Results

For the timber frame structure an additional aspect is relevant. Namely the issue described in Chapter 3 regarding the position of the analytical lines relative to the physical model in Revit. Since several structural elements are joined in the frame structure, it is important that the analytical representation corresponds with the physical model.

In order to show which specific parameters in each group of parameters the S-BIM tools must be able to handle some initial and independent calculations are made. This is done according to the design criteria in Eurocode 5. The calculations are as far as possible made both by hand and by StaadPro. Some calculations are only made by hand, since it is not possible to make a code check for tapered beams in StaadPro.

### 4.3 Basis of tests

The timber frame structure from Krafthallen in Tromsø is built of traditional beams and tapered beams with varying cross section. The beams are supported by columns in four points. The total width of the frame is 34.83 m whereas the biggest span is 17.75 m [Bell, 2005]. A sketch of the timber frame structure is shown in Figure 4.4.



**Figure 4.4** Nodes and elements in the timber frame structure.

The timber frame structure is subjected to line loads of  $g = 7,5 \text{ kN/m}$  and  $q = 15,0 \text{ kN/m}$  corresponding to self weight of the roof and snow load, respectively. The width of the beams is 200 mm and the height is varying from 220 mm to 1250 mm. The width and height of the columns varies from 150 mm to 260 mm. All elements are modelled as glulam timber G136c<sup>1</sup>.

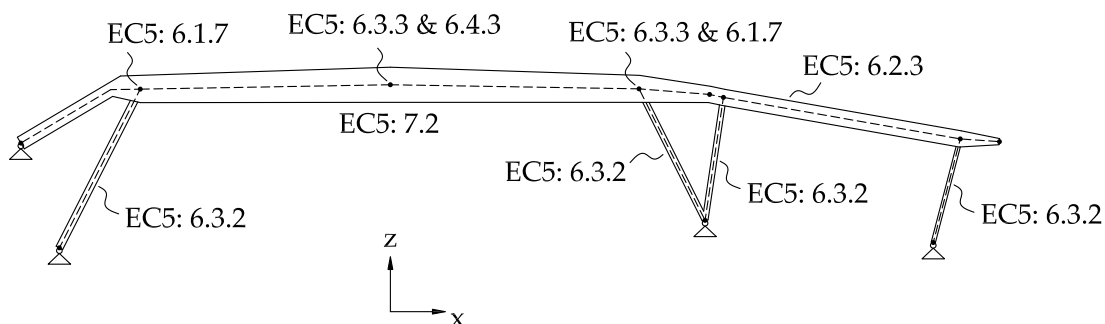
There are different design criteria for the elements in the timber frame structure. The relevant design criteria are found by StaadPro and hand calculations cf. DS/EN 1995-1-1 [2007]. The design criteria are as follows:

<sup>1</sup>Note that the timber code check in StaadPro only supports timber strength classes according to EN 338:2003 [2003]. Thus the timber is modelled as Hardwood D40 in the StaadPro code check.

#### 4. Analysis of S-BIM tools – timber frame structure

- EC5: 6.3.2 Columns subjected to combined compression and bending
- EC5: 6.3.3 Beams subjected to combined bending and compression
- EC5: 6.2.3 Combined bending and axial compression
- EC5: 6.1.7 Shear
- EC5: 6.4.3 Double tapered, curved and pitched cambered beams
- EC5: 7.2 Limiting values for deflections of beams

The elements or nodes to which the design criteria are relevant are shown in Figure 4.5.



**Figure 4.5** Relevant design criteria for the timber frame structure.

The parameters needed to evaluate the design criteria are presented in Appendix F.1.

As it was the case for the simple structures, no partial factors are applied to the loads, since the size of the load is irrelevant in order to evaluate the S-BIM tools and the results obtained. Also no partial factors should be applied to the material properties. However, partial factors according to DS/EN 1995-1-1 [2007] are applied since they are defined by default in Robot and StaadPro.

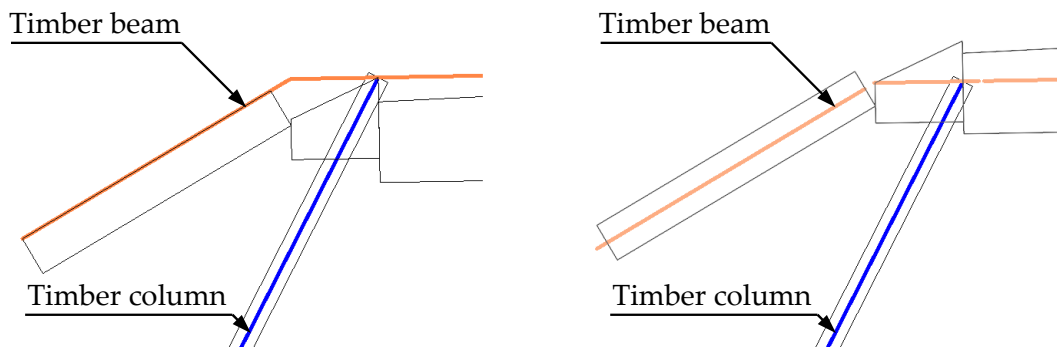
In order to test the applicability of updating backwards to Revit changes are made one at a time in Robot and StaadPro respectively. The tests contain the following changes:

- The cross section of a column is changed from  $200 \times 200$  mm to  $260 \times 260$  mm
- The length of a beam is changed with 300 mm
- The material is changed from Gl36c to Gl32c
- The load corresponding to self weight of the roof is changed from 7.5 kN/m to 8.5 kN/m
- One of the supports are changed from pinned to fixed

The changes are chosen to show how well the S-BIM tools handle the groups of parameters presented in Section 4.2 when updating backwards to Revit.

### 4.3.1 Modelling and handling issues

Revit has no default family for tapered beams. Thus a new family for tapered beams must be created manually in Revit. This is done relatively simple. But it is not possible to manually define the positioning of the analytical representation of the tapered beam. I.e. it is impossible to create a family with a satisfactory analytical representation of the tapered beams. Either the analytical line is placed in the top of the element or in the middle of the element but in a position that does not correspond with the centre line through the element. This issue is shown in Figure 4.6.



**Figure 4.6** Screenshot from Revit. Left: Analytical model positioned in the top of the beams. Right: Analytical model positioned in the centre of the beams.

Neither of the solutions shown in Figure 4.6 provides a satisfactory physical representation of the frame structure. However, the solution with the analytical lines placed in the top of the beam elements provides a satisfactory analytical representation. Thus, this model is used for testing the applicability of the S-BIM tools, with the following results:

- **Revit add-on tool (RVT add-on)**

When trying to test the Revit add-on tool, it does not load, but gives a warning about incorrect geometric properties. I.e. it is not possible to analyse tapered elements in this add-on tool.

- **Direct link from Revit to Robot and backwards (RVT ↔ RSA)**

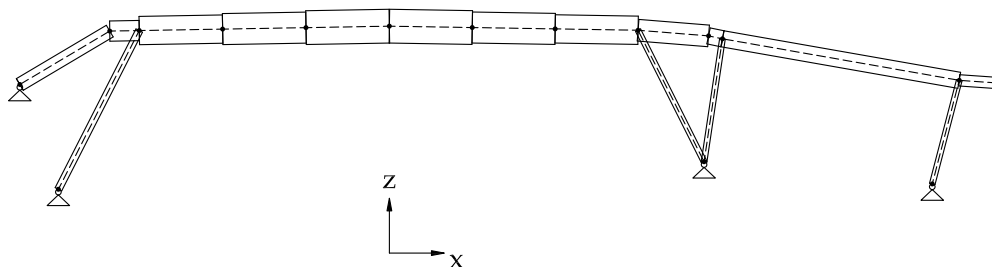
It is not possible to export the cross section of the tapered beams to Robot.

- **Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)**

None of the cross sections are exported to StaadPro. StaadPro does not support code check of tapered timber beams.

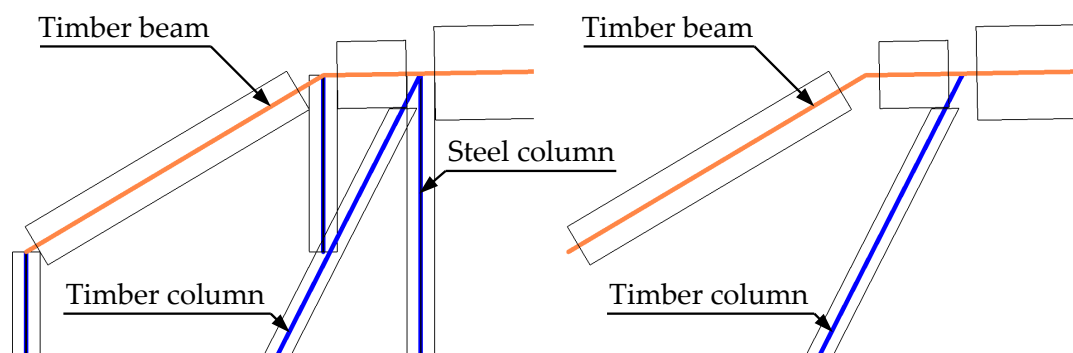
According to the above described lacks, the tapered beams are modelled as pieces of beams with constant rectangular cross section as shown in Figure 4.7.

The changed parameters for this model are presented in Appendix F.2.



**Figure 4.7** The timber frame structure with beams of constant rectangular cross section.

Since it is not possible to define node points or to snap to crossings between levels and grid lines in Revit, steel columns have been added instead of nodes and the timber beams and columns are drawn between the top points of the steel columns. This provides a satisfactory analytical representation of the timber frame. The steel columns are only added due to the modelling limitations in Revit, hence they are not included in the structural analysis. The steel columns are shown in Figure 4.8.



**Figure 4.8** Screenshot from Revit. Left: Columns are added to the nodes. Right: The analytical model is correct.

As shown in Figure 4.8 the analytical representation of the beams is convergent with the centreline. Thus the positioning of the elements should not be an issue in Robot or StaadPro.

### 4.4 Results of tests

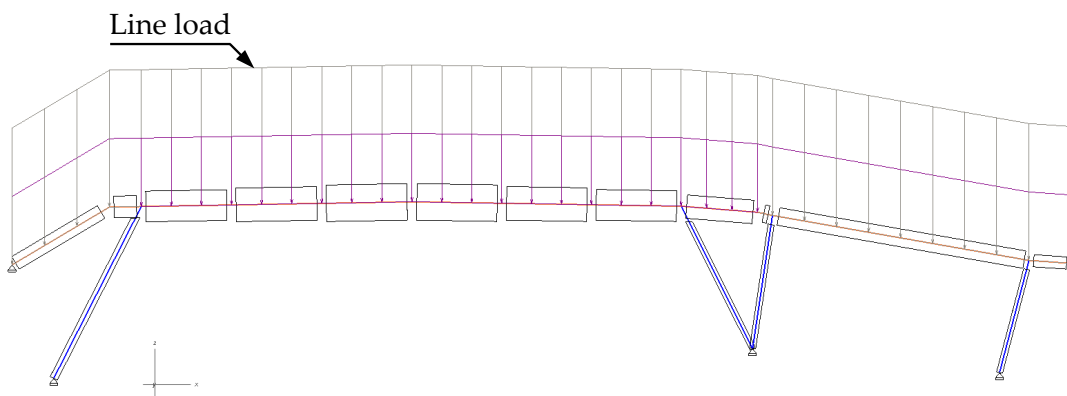
Based on the design criteria described in Section 4.3, the design parameters in Appendix F.1 and F.2, and the procedure described in Appendix F.3, the applicability of the S-BIM tools are tested by means of the timber frame structure. The results are given in Table 4.1 on page 52.

Note that the design criteria are defined for the original structure with tapered beams, whereas the tests are based on the Revit model where the tapered beams are replaced with pieces of beams with constant rectangular cross section.

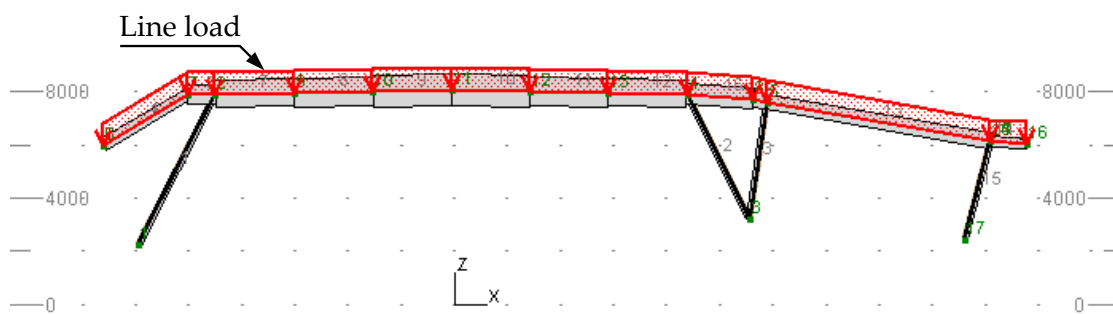
A screenshot of the timber frame structure modelled in Revit is shown in Figure 4.9. After using the add-on tool and the direct links to Robot and StaadPro the timber frame structure appears as shown in Figure 4.10, 4.11 and 4.12.

The analytical and physical representation are consistent in the four models.

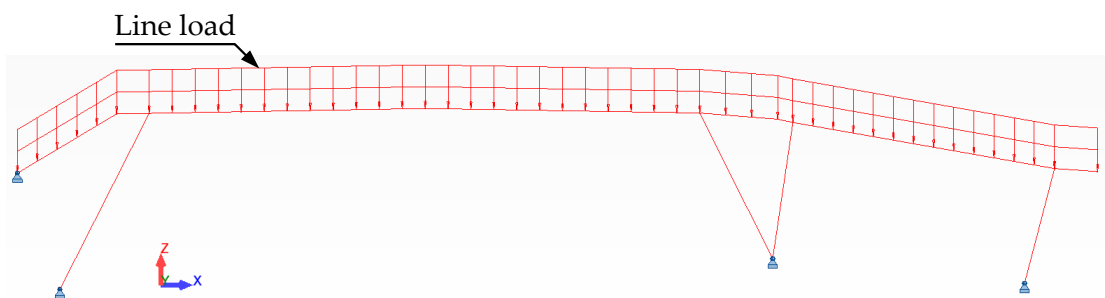
Note that in both Robot and StaadPro the anisotropic timber is treated as isotropic.



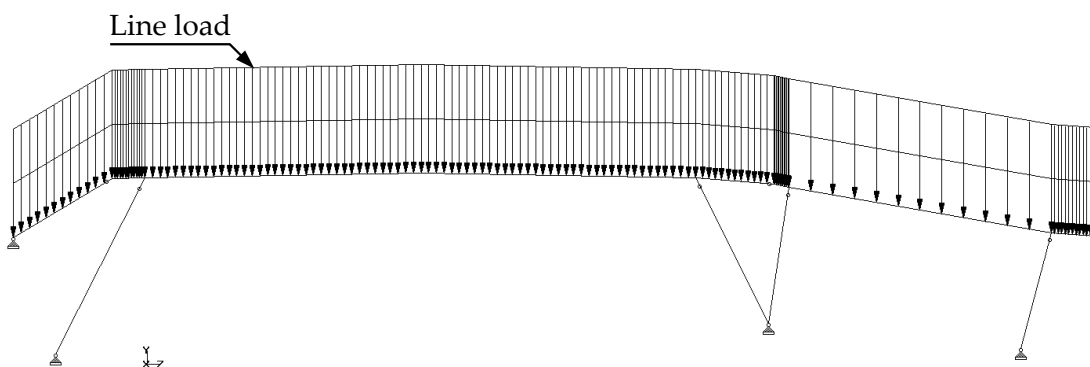
**Figure 4.9** Statical system and line load in Revit.



**Figure 4.10** Statical system and line load in the Revit add-on tool.



**Figure 4.11** Statical system and line load in Robot.



**Figure 4.12** Statical system and line load in StaadPro.

#### 4. Analysis of S-BIM tools – timber frame structure

|   | RVT | RVT<br>add-on   | RVT<br>↓<br>RSA | RVT<br>↑<br>RSA | RVT<br>↓<br>SPro | RVT<br>↑<br>SPro |
|---|-----|-----------------|-----------------|-----------------|------------------|------------------|
| <b>1. Section properties</b>                    |     |                 |                 |                 |                  |                  |
| Height $h$                                      | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Width $b$                                       | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Area $A$  | ✓   | ✓               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Moment of inertia $I_y$                         | ✓   | ✓               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Elastic modulus $W_{el,y}$                      | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| <b>2. Geometry</b>                              |     |                 |                 |                 |                  |                  |
| Length $l$                                      | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| <b>3. Material properties</b>                   |     |                 |                 |                 |                  |                  |
| Characteristic bending strength $f_{m,k}$       | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Characteristic tensile strength $f_{t,0,k}$     | ÷   | ÷               | ✓ <sup>3</sup>  | 1               | ÷                | 1                |
| Characteristic tensile strength $f_{t,90,k}$    | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Characteristic compressive strength $f_{c,0,k}$ | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Characteristic shear strength $f_{v,k}$         | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ÷                | ÷                |
| Characteristic modulus of elasticity $E_k$      | ✓   | ✓               | ✓               | ÷ <sup>2</sup>  | ✓                | ÷                |
| Characteristic value of shear modulus $G$       | ✓   | ÷               | ✓               | ÷ <sup>2</sup>  | ✓                | ÷                |
| Density $\rho$                                  | ✓   | ✓               | ✓               | ÷ <sup>2</sup>  | ✓                | ÷                |
| <b>4. Loads</b>                                 |     |                 |                 |                 |                  |                  |
| Duration  | ÷   | ÷               | ✓ <sup>4</sup>  | 1               | ✓ <sup>4</sup>   | 1                |
| Magnitude $q, g$                                | ✓   | ✓               | ✓               | ÷               | ✓ <sup>6</sup>   | ÷                |
| Position  | ✓   | ✓               | ✓ <sup>5</sup>  | ÷               | ✓ <sup>6</sup>   | ÷                |
| Combination                                     | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| <b>5. Boundary conditions</b>                   |     |                 |                 |                 |                  |                  |
| Pinned  | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| Releases  | ✓   | ✓ <sup>7</sup>  | ✓               | ÷               | ✓                | ÷                |
| <b>6. Design data</b>                           |     |                 |                 |                 |                  |                  |
| Allowable bending stress $f_{m,d}$              | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| Allowable tensile stress $f_{t,0,d}$            | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| Allowable tensile stress $f_{t,90,d}$           | ÷   | ÷               | ÷               | 1               | ÷                | 1                |
| Allowable normal stress $f_{c,0,d}$             | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| Allowable shear stress $f_{v,d}$                | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| Modification factor $k_{mod}$                   | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| Instability factor $k_{c,y}$                    | ÷   | ÷               | ✓ <sup>8</sup>  | 1               | ÷                | 1                |
| Factor for lateral buckling $k_{crit}$          | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| Volume factor $k_{vol}$                         | ÷   | ÷               | ÷ <sup>9</sup>  | 1               | ÷                | 1                |
| Factor for distribution of stresses $k_{dis}$   | ÷   | ÷               | ÷ <sup>9</sup>  | 1               | ÷                | 1                |
| Service class                                   | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| <b>7. Results</b>                               |     |                 |                 |                 |                  |                  |
| Section forces                                  | ÷   | ✓ <sup>10</sup> | ✓ <sup>10</sup> | 1               | ÷                | 1                |
| EC5: 6.3.2                                      | ÷   | ÷               | ✓ <sup>11</sup> | 1               | ÷                | 1                |
| EC5: 6.3.3                                      | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| EC5: 6.2.3                                      | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| EC5: 6.1.7                                      | ÷   | ÷               | ✓               | 1               | ÷                | 1                |
| EC5: 6.4.3                                      | ÷   | ÷               | ÷               | 1               | ÷                | 1                |
| EC5: 7.2  | ÷   | ✓               | ✓               | 1               | ÷                | 1                |

**Table 4.1** Test results for the timber frame structure. ✓ means no problems and ÷ means that it does not work or that the parameter/feature is not available.



Notes to Table 4.1:

- 1) This parameter is not available in Revit.
- 2) When changing the cross section in Robot the column is stored in a wrong family in Revit. If the new cross section already exists in Revit the application will choose the right family. When changing the material properties, it only works if the material added in Robot already exists in Revit. If the new material does not exist in advance in Revit it does not work.
- 3) This parameter is only available since Robot has Gl36c in its default material library.
- 4) Load duration is not available in Revit and must be added manually before analyses are performed.
- 5) The loads are outside element 12 and must be redefined.
- 6) There are no loads at element 10 and the loads at element 12 are placed wrong. Therefore the loads at element 10 and 12 must be redefined.
- 7) The releases are only correct if the beams are drawn from left to right. For the columns the releases are only correct if the columns slant to the right.
- 8) The instability factor  $k_{c,y}$  are calculated in a different manner than given in DS/EN 1995-1-1 [2007], which provides values that are approximately half of the hand calculations by DS/EN 1995-1-1 [2007].
- 9) This parameter is needed for tapered beams, thus not given here, since the tapered beams are replaced with pieces of beams with constant cross section.
- 10) Some elements are randomly chosen for check of section forces. The results from both the Revit add-on tool and Robot vary slightly but are quite consistent with the results obtained initially by StaadPro.
- 11) The utilization of the columns is higher, than for the hand calculations, since the instability factor  $k_{c,y}$  are lower in Robot than for the hand calculations by DS/EN 1995-1-1 [2007] as described in note 8.

As shown in Table 4.1 the section properties are not transferred from Revit to StaadPro. Therefore they must be defined manually, which is rather easily done, before analysis can be performed in StaadPro.

Regarding the material, the *SI Xchange* link does not support timber materials as described in Section 3.6. However the modulus of elasticity, the shear modulus and the density are transferred from Revit to StaadPro, whereas strengths parameters must be defined manually to perform a code check. In StaadPro it is not possible to define glulam timber Gl36c since the application only supports timber strength classes according to EN 338:2003 [2003]. Thus the timber is modelled as Hardwood D40 in the StaadPro code check.

When section properties are assigned to the elements in StaadPro it is possible to get the section forces and the deflection of the timber frame structure. Since the original structure with tapered beams and the modified structure with pieces of beams with constant rectangular cross section both are modelled in StaadPro, it is possible to check the influence of the modification. In Table 4.2 some randomly chosen results for the timber frame structure are shown.

| Position  |   | Tapered beams | Pieces of beams |     |
|-----------|---|---------------|-----------------|-----|
| Element 2 | M | 0.65          | 0.65            | kNm |
|           | N | 274.1         | 280.0           | kN  |
| Element 6 | M | 0.3           | 0.3             | kNm |
|           | N | 422.0         | 415.0           | kN  |
| Node 5    | M | 728.0         | 733.0           | kNm |
|           | N | 153.5         | 149.1           | kN  |
|           | w | 63.3          | 63.7            | mm  |
| Node 6    | V | 220.4         | 219.4           | kN  |

**Table 4.2** Comparison of randomly chosen section forces and deflection for the timber frame structure modelled in *StaadPro*.

From Table 4.2 it can be seen that the difference between the results obtained for the timber frame structure modelled with tapered beams and modelled with pieces of beams with constant rectangular cross section are small. This shows that the modification does not have any appreciable influence of the results.

Finally it should be noticed that if the strengths parameters are defined manually in *StaadPro* the application check the same design criteria as *Robot* and gives almost the same results.

### 4.5 Evaluation of tests

Based on the results presented in Table 4.1 an evaluation of the applicability of the S-BIM tools in relation to the timber frame structure is made.

#### Revit add-on tool (RVT add-on)

★ ☆ ☆ ☆ ☆

The Revit add-on tool gets one star because it is useful in relation to compute the section forces and deflection. On the other hand it is not possible to assess the design criteria with the Revit add-on tool.

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

★ ★ ★ ☆ ☆

The direct link gets three stars because it is possible to exchange almost all relevant data from Revit to Robot. However the load on one element was not transferred correctly. Pre-loading the needed cross section and material properties is needed in Revit, in order to update the cross section and material properties.

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

★ ★ ☆ ☆ ☆

The link gets two stars because it is useful in relation to transfer geometry, material properties, loads and supports from Revit to StaadPro, whereas the cross section must be defined manually. If this is done StaadPro checks the same design criteria as Robot and almost gives the same results. The link from StaadPro to Revit is useless since no information can be exchanged this way.

## 4.6 Subconclusion

In this chapter a timber frame structure from Krafthallen in Tromsø has formed the basis of the evaluation of the applicabilities of the tested S-BIM tools.

The timber frame structure was chosen for this study to see if the S-BIM tools can handle a timber frame structure which is more advanced than the simple structures in Chapter 3. The structure is more advanced in the sense that several elements are joint together. Further neither of the elements is vertical nor horizontal and several of the beams are tapered with varying section height. Finally it is an advantage if the S-BIM tools are able to handle structures with e.g. varying beam height since this is a ordinary type of structure.

Tapered beams could not be modelled satisfactorily in Revit. Neither could the tapered cross sections be exported to any of the S-BIM tools. Hence the tapered beams in the timber frame have been modelled as pieces of beams with constant rectangular cross section as an approximation.

### **Revit add-on tool (RVT add-on)**

As it was the case for the simple structures in Chapter 3 it is concluded that the Revit add-on tool is capable of calculating section forces and deflection. This gives an overview of the structure for a feasibility study.

### **Direct link from Revit to Robot and backwards (RVT ↔ RSA)**

As it was the case for the timber column in Chapter 3, this direct link makes it possible to evaluate the timber structure according to Eurocode 5. A full one-way linking is possible whereas it is only possible to update some of the relevant parameters from Robot to Revit.

### **Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)**

As it was the case for the timber column in Chapter 3 it has not been possible to exchange section properties. This was expected since the links *SI Xchange* currently only supports steel and concrete materials. However the link is useful in relation to geometry, material properties, loads and supports. It has not been possible to update anything backwards from StaadPro to Revit.

Both direct links had an issue with the position of the loads on one of the elements in the timber frame structure. This could be caused by a modelling error in Revit, but it has not been possible to eliminate this issue.

Based on the tests performed so far it is still found that the direct link *Integration with Robot Structural Analysis* is most preferable. Though it should be kept in mind that the *SI Xchange* link was not developed for timber structures. Thus a steel structure is treated in the next chapter.



## Analysis of S-BIM tools – 3D steel structure

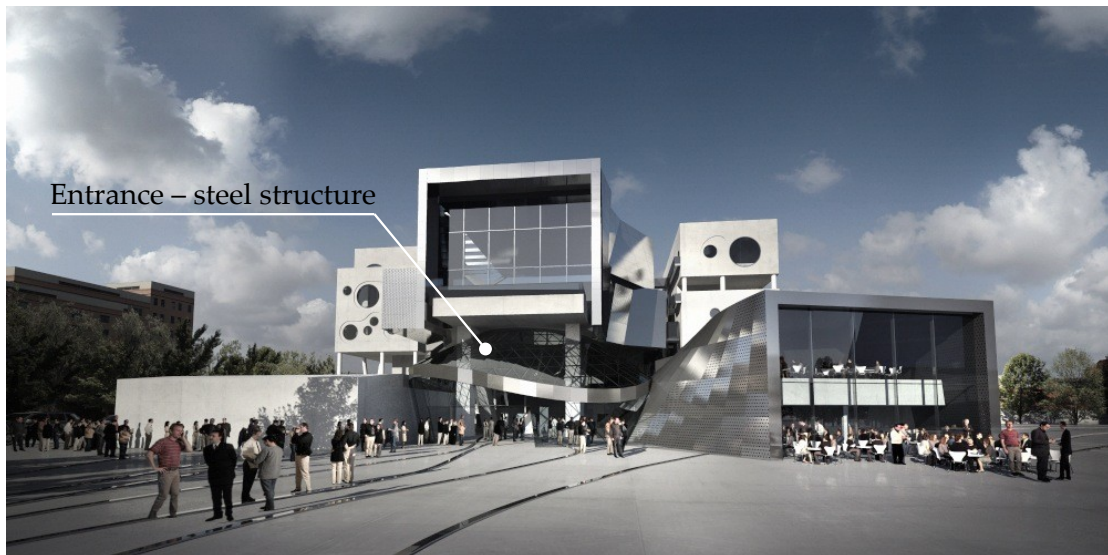
---

In this chapter the step before the data exchange between the S-BIM software and the FEM software is considered. Three of the S-BIM tools, presented in Section 2.6, are analysed through a three-dimensional steel structure. Following an evaluation of the S-BIM tools are given.

---

### 5.1 Introduction

In this chapter the applicability of each S-BIM tool is tested with a three-dimensional steel structure from the House of Music in Aalborg, Denmark. The House of Music is approximately 20,000 m<sup>2</sup> and includes among other things a concert hall for 1,300 guests, a rhythmical hall, a classical hall and facilities for different educations within music. The project design of the House of Music is still going on. The House of Music is shown in Figure 5.1. The project is expected to be finished at the end of 2012 [Rambøll Danmark A/S].



**Figure 5.1** *The House of Music in Aalborg [CoopHimmelB(l)au, 2010].*

The House of Music will consist of structures in concrete and steel. The three-dimensional steel structure considered in this project is a part of the entrance to the House of Music. An overview of the steel structure is shown in Figure 5.2. The structure is chosen to see if the S-BIM tools can handle a structure which is more advanced than the timber frame structure in Chapter 4.

The structure is more advanced in the sense that several elements are joint together in three dimensions and that the overall form of the structure does not follow any traditional geometric shape.

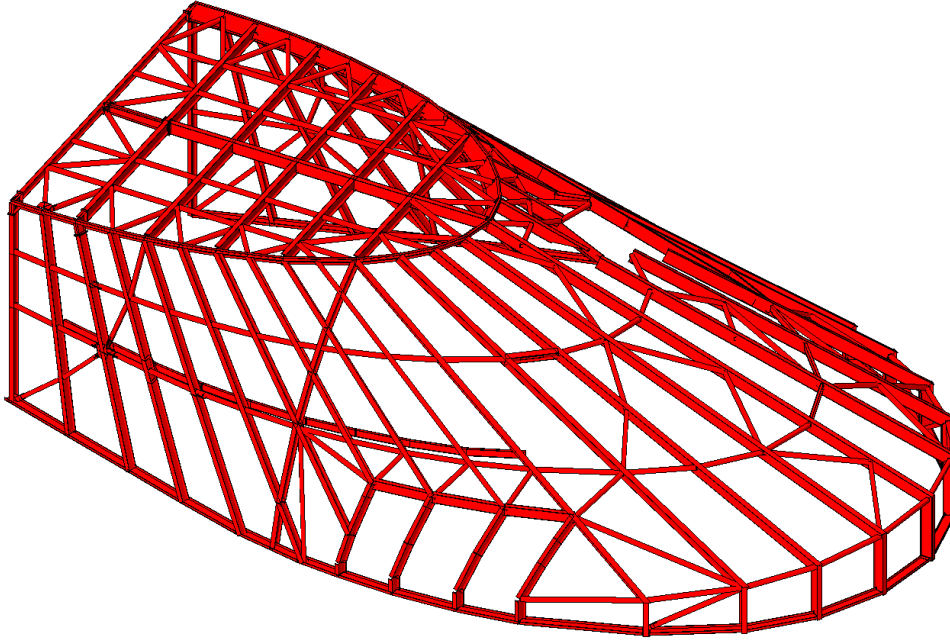


Figure 5.2 Steel structure from the entrance of the House of Music in Aalborg.

### 5.2 Methods of analysis

The specific method used in this chapter corresponds with the method used in Chapter 3 and 4. However an additional aspect of the data exchange is considered since the three-dimensional steel structure originally has been modelled by Rambøll in *Tekla Structures* [Tekla, 2010].

In order to be able to perform the tests of the S-BIM tools the steel structure is attempted imported to Revit. Thus the information flow treated in this chapter appears as illustrated in Figure 5.3.

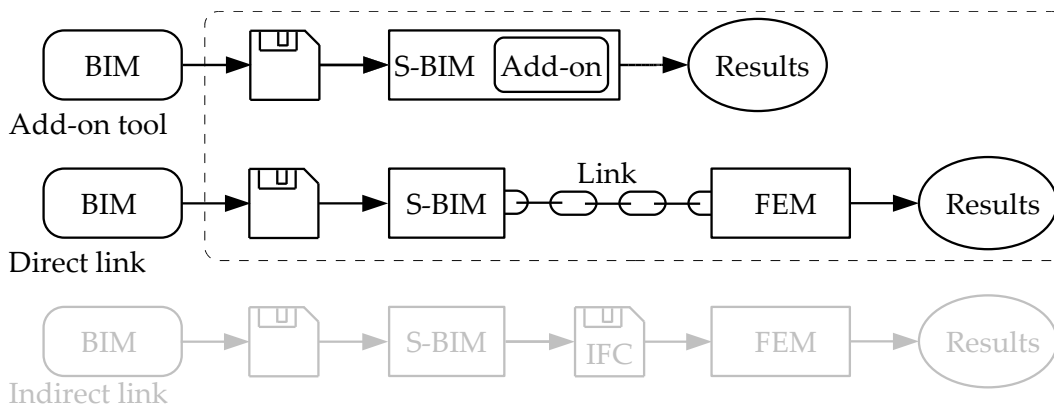


Figure 5.3 Information flow from the BIM (model) to the results of calculations.

The following methods are used for import to Revit:

- Import to Revit via a DWG file (Tekla  $\xrightarrow{\text{DWG}}$  RVT)
- Import to Revit via an IFC file (Tekla  $\xrightarrow{\text{IFC}}$  RVT)
- Import to Revit via a CIS/2 file (Tekla  $\xrightarrow{\text{CIS/2}}$  RVT)

When an analytical representation of the steel structure is available in Revit the following S-BIM tools are tested:

- Revit add-on tool (RVT add-on)
- Direct link from Revit to Robot and backwards (RVT  $\leftrightarrow$  RSA)
- Direct link from Revit to StaadPro and backwards (RVT  $\leftrightarrow$  SPro)

It should be noticed that the tested add-on tool *Revit Extensions, Simulation - Static Analysis of Frames* only work for plane structures. Since the steel structure is three-dimensional only some chosen elements are analysed via the add-on tool.

The parameters which the S-BIM tools must be able to handle are arranged in the same groups as described in Chapter 3 and 4. These groups of parameters are still:

1. Section properties
2. Geometry
3. Material properties
4. Loads
5. Boundary conditions
6. Design data
7. Results

In addition to the described groups of parameters the S-BIM tools must be able to handle the issue concerning the analytical model. Since several structural elements are joined in the structure, it is important that the analytical representation corresponds with the physical model. This can be a problem since the analytical line of a beam is placed in the top of the beam by default in Revit but in the centre of the beam in Robot and StaadPro.

In order to show which specific parameters in each group of parameters the S-BIM tools must be able to handle some initial and independent calculations are made. This is done according to the design criteria in Eurocode 3. In this chapter the calculations are made by hand and Robot.

### 5.3 Basis of tests

The steel structure from the House of Music in Aalborg is built of traditional steel beams and columns as well as a few special profiles, i.e. mainly IPE, SHS and UNP profiles. The structure is shown in Figure 5.4 and is approximately 35 m long, 23 m wide and 9.5 m high.

The steel structure is subjected to self weight and snow load. The self weight is set to  $1.5 \text{ kN/m}^2$  at the facade and  $2 \text{ kN/m}^2$  at the roof. The snow load is set to  $0.72 \text{ kN/m}^2$ .

All elements are modelled as steel quality S355.

Three elements are randomly chosen for code check. A horizontal beam, a vertical column and a slanted beam. The three elements have different positions, different relation to the adjacent elements and are affected by different loads. The elements 106, 176 and 381 are highlighted in Figure 5.4. These elements might not be the most critical elements, however the utilization of each member is not important since design and optimization of the structure is not the objective of this study.

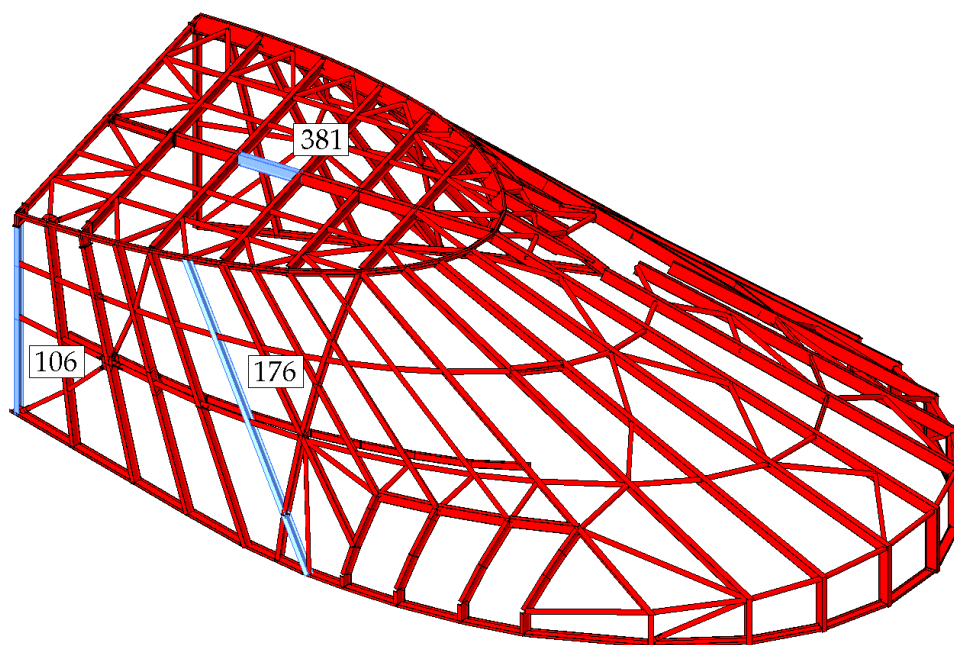


Figure 5.4 Steel structure with elements for code check.

There are different design criteria for the selected elements in the steel structure. The relevant design criteria are found by Robot and hand calculations cf. BS EN 1993-1-1:2005 [2005]. The design criteria are as follows:

- EC3: 6.2.5 Bending moment
- EC3: 6.2.6 Shear
- EC3: 6.2.6-7 Shear - Torsion
- EC3: 6.3.3 Uniform members in bending and axial compression

The elements to which the design criteria are relevant are shown in Table 5.1.



| Design criterion | Element |     |     |
|------------------|---------|-----|-----|
| EC3: 6.2.5       | 106     | 176 | 381 |
| EC3: 6.2.6       | 106     |     | 381 |
| EC3: 6.2.6-7     |         | 176 |     |
| EC3: 6.3.3       | 106     | 176 | 381 |

**Table 5.1** *Design criteria and the elements to which they are employed.*

The parameters needed to evaluate the design criteria are presented in Appendix G.1.

As it was the case for the previous structures, no partial factors are applied to the loads, since the size of the load is irrelevant in order to evaluate the S-BIM tools and the results obtained. Also no partial factors should be applied to the material properties. However, partial factors according to BS EN 1993-1-1:2005 [2005] are applied since they are defined by default in both Robot and StaadPro.

In order to test the applicability of updating backwards to Revit changes are made one at a time in Robot and StaadPro respectively. The tests contain the following changes:

- The cross section of a column is changed from IPE400 to IPE500
- The length of a beam is changed by moving a pinned support 100 mm
- The material is changed from S355 to S235
- The snow load on a slanted beam is changed from 5.40/2.34 kN/m to 6.40/3.34 kN/m
- One of the supports are changed from pinned to roller

The changes are chosen to show how well the S-BIM tools handle the groups of parameters presented in Section 5.2 when updating backwards to Revit.

### 5.3.1 Data exchange to Revit from Tekla Structures

So far, the focus has been on the exchange of data between the S-BIM software and the FEM software. In order to review the information flow from the BIM (model) to the results of calculations, the exchange of data from the BIM (model) to the S-BIM software also needs to be investigated.

Like the data exchange between the S-BIM software and the FEM software, the data exchange between the BIM (model) and the S-BIM software is a huge subject. Thus it will only be investigated briefly. Since the three-dimensional steel structure has been modelled by Rambøll in *Tekla Structures* the data exchange from Tekla to Revit will be treated.

The three-dimensional steel structure has been available to the authors as a DWG file (\*.dwg), an IFC file (\*.ifc) and a CIS/2 file (\*.stp).

In order to be able to exchange data between the S-BIM software and the FEM software an analytical representation of the three-dimensional steel structure is needed. Therefore the structure is imported to Revit from the three file formats (\*.dwg), (\*.ifc) and (\*.stp). This is done to clarify which file format provides the best representation of the structure in Revit. A satisfactory representation enables a continuous workflow without the need for remodelling the entire structure.

The procedure leading to the results obtained in Revit, after import from Tekla Structures by use of the different file formats, are described in Appendix G.2. The results are described in the following:

- **Import to Revit via a DWG file (Tekla  $\xrightarrow{\text{DWG}}$  RVT)**  
The three-dimensional steel structure from the DWG file appears as one object in Revit and each of the elements are only represented by lines. This is a rather inadequate representation of the structure since the elements should be geometric objects with a corresponding analytical model.
- **Import to Revit via an IFC file (Tekla  $\xrightarrow{\text{IFC}}$  RVT)**  
The three-dimensional steel structure from the IFC file appears as objects with the correct geometry in Revit. However there is no analytical model linked to the IFC objects and it is not possible to convert the objects to Revit objects with analytical lines. I.e. it is not possible to define the analytical model based on the IFC file in Revit.
- **Import to Revit via a CIS/2 file (Tekla  $\xrightarrow{\text{CIS/2}}$  RVT)**  
Using the CIS/2 file gives both the analytical and the physical representation of the three-dimensional steel structure in Revit. However only 132 of 324 elements are imported in Revit. This makes the model rather incomplete. Mainly the SHS profiles are missing.

The exchange of data from the BIM (model) to the S-BIM software is a part of the information flow in the structural design phase. The next part of the information flow is the data exchange between the S-BIM software and the FEM software. To obtain an efficient information flow, and hereby a continuous structural design process, the exchange should work well in both parts of the process. This little test has shown that none of the three file formats gives a satisfactory representation of the three-dimensional steel structure after import to Revit. This can be due to the file formats or due to Revit. Either way there is a lack in the information flow in this first part of the process.

In the following the second part of the process i.e. the data exchange between the S-BIM software and the FEM software will be investigated in details.

### 5.3.2 Modelling and handling issues

As described above import of the (\*.dwg), the (\*.ifc) and the (\*.stp) file in Revit did not give a satisfactory representation of the three-dimensional steel structure in Revit. Therefore the structure has to be adapted to a great extent or to be modelled from the bottom. However the steel structure has been available for the authors in the Robot file format (\*.rtd) since the structure was modelled in Robot by Rambøll.

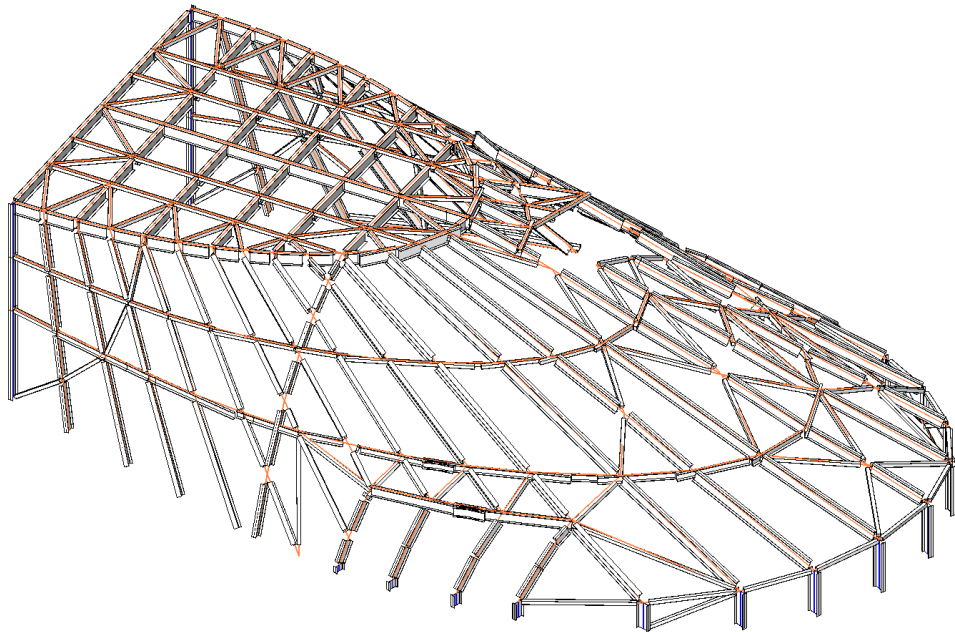
The (\*.rtd) file is used in order to get a complete model of the three-dimensional steel structure which can form the basis of the tests of the S-BIM tools. In Robot the model is saved as a (\*.stp) file which afterwards is imported to Revit.

- **Import to Revit via a CIS/2 file (RSA  $\xrightarrow{\text{CIS/2}}$  RVT)**  
During the import it is chosen to import the analytical model and thereby not the drawing model. According to Revit, the model contains 421 elements of which 416 elements are imported. There are one error and ten warnings in connection with the import. The error is due to one of the missing elements. The missing elements are identified.

- **Integration with Robot Structural Analysis (RSA → RVT)**

To get the missing elements into Revit the import of the (\*.stp) file is followed by an integration with Robot which is possible now that the model exist in Revit. The integration is only performed for the elements which were not imported at the first time.

After going through the procedure described above, the three-dimensional structure appears in Revit as shown in Figure 5.5.

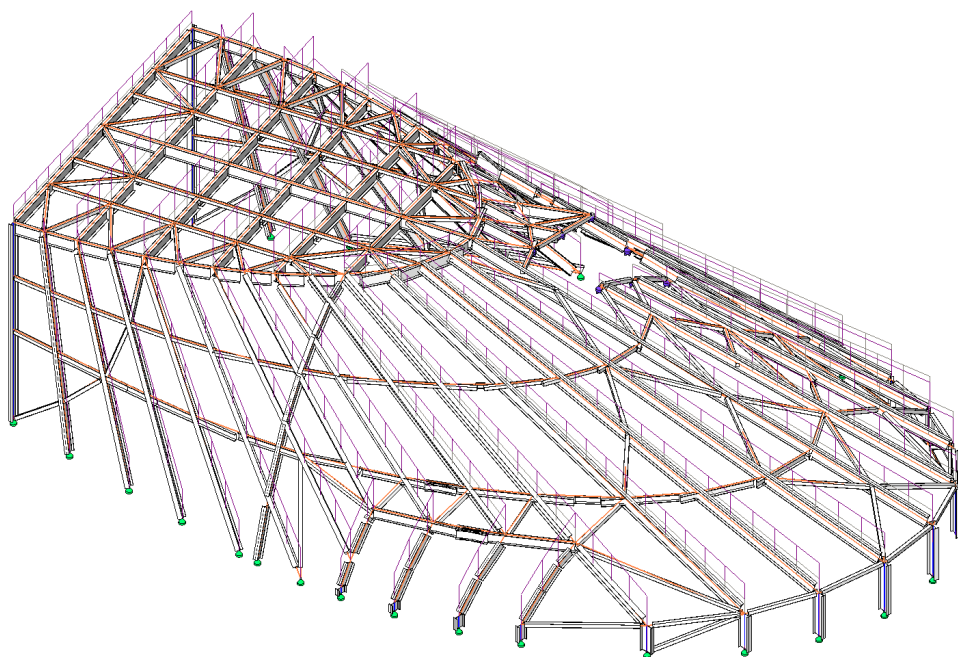


**Figure 5.5** *The three-dimensional steel structure after import to Revit.*

In order to perform the tests of the S-BIM tools some adjustments have to be made. Afterwards loads and boundary conditions are added to the model since these were not included in the import procedure. The following adjustments are made:

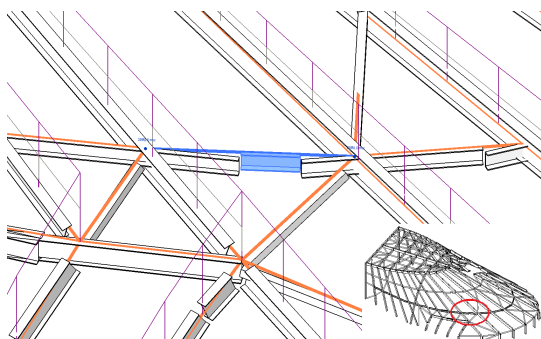
- The columns and the slanted beams which form the main structure should be one continuous element from the top of the structure to the bottom of the structure. During the import to Revit the elements were divided into several elements according to the position of braces. This is corrected manually in Revit.
- The material should be steel type S355. During the import to Revit the steel was changed from S355 to S345. This is corrected manually in Revit.
- The releases in each end of the elements were changed during the import to Revit. It seems like several of the releases that were fixed in Robot are free in Revit and opposite. Thus, all of the releases are checked and corrected manually in Revit.
- The loads are added manually in Revit, since they were not imported from Robot.
- The supports are defined manually in Revit, since they were not imported from Robot. There are 7 rollers and 22 pinned supports.

After the adjustments are made the three-dimensional structure appears as shown in Figure 5.6.

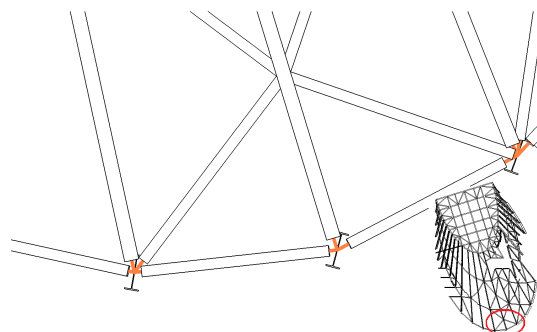


**Figure 5.6** *The three-dimensional steel structure after some adjustments in Revit.*

Figure 5.6 shows a satisfactory analytical representation of the three-dimensional steel structure. However there are some errors in the physical representation. Two examples of this are shown in Figure 5.7 and 5.8.



**Figure 5.7** *Three overlapping beams in Revit. The analytical line of the elements is positioned in the top of the elements.*



**Figure 5.8** *The rotation of the columns is wrong in Revit. They should have been parallel to the adjacent slanted beams.*

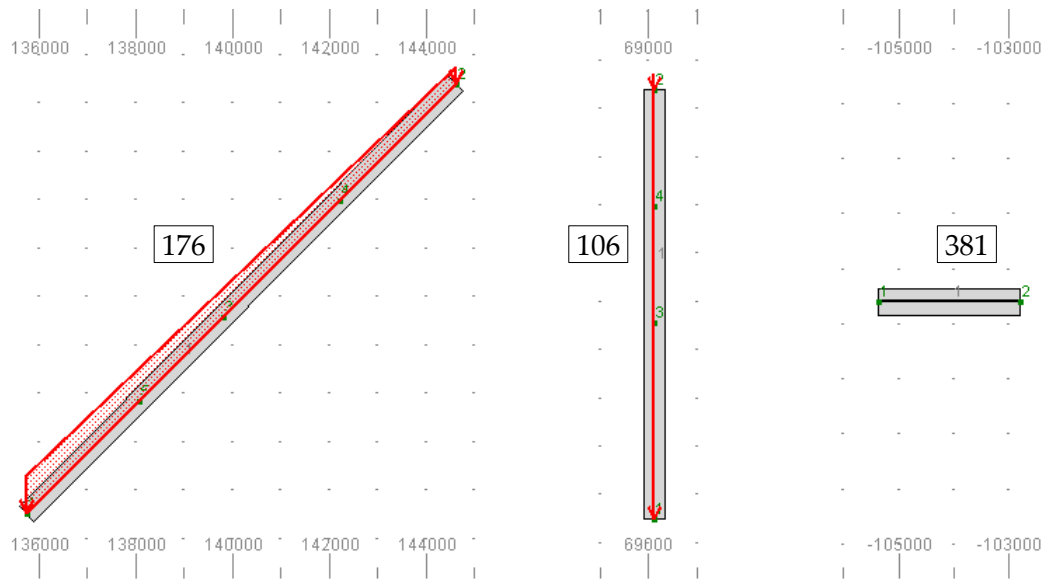
Since only the analytical model influences the results of the tests, the physical model is accepted despite the errors.

### 5.4 Results of tests

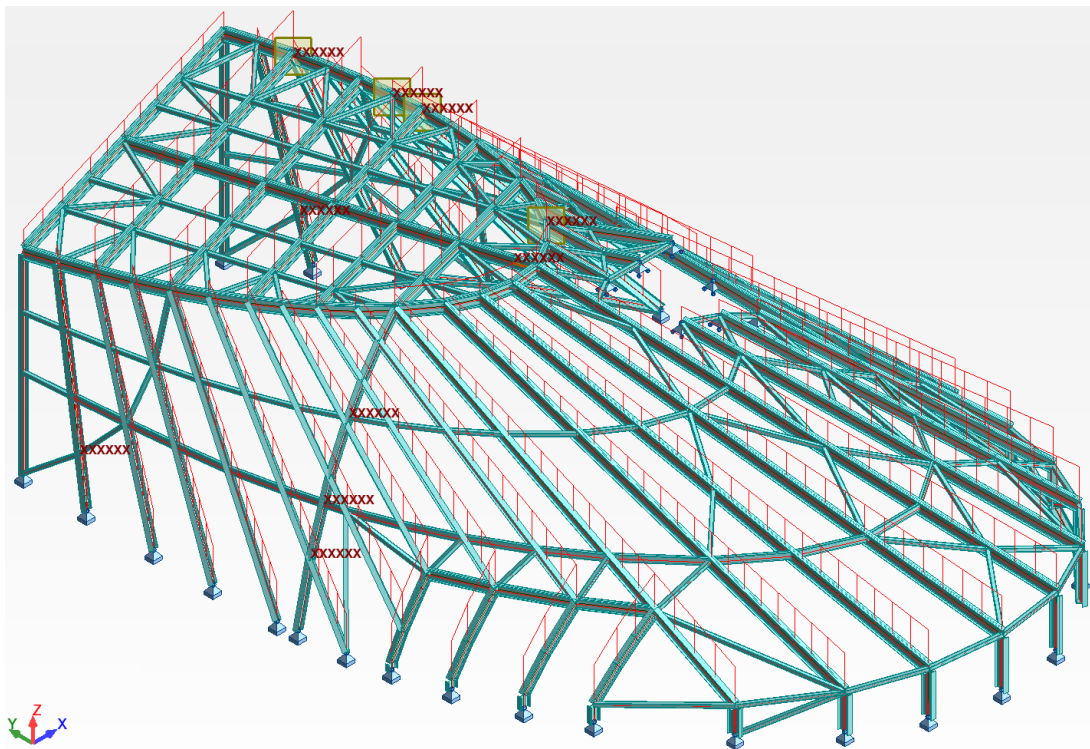
Based on the design criteria described in Section 5.3, the design parameters in Appendix G.1 and the procedure described in Appendix G.3 the applicability of the S-BIM tools are tested by means of the three-dimensional steel structure. The results are given in Table 5.2 on page 67.

After using the add-on tool and export via the direct link to Robot the steel structure appears as

shown in Figure 5.9 and 5.10. Since the steel structure is three-dimensional and the add-on tool only works for plane structures, only the chosen elements are analysed via the add-on tool.



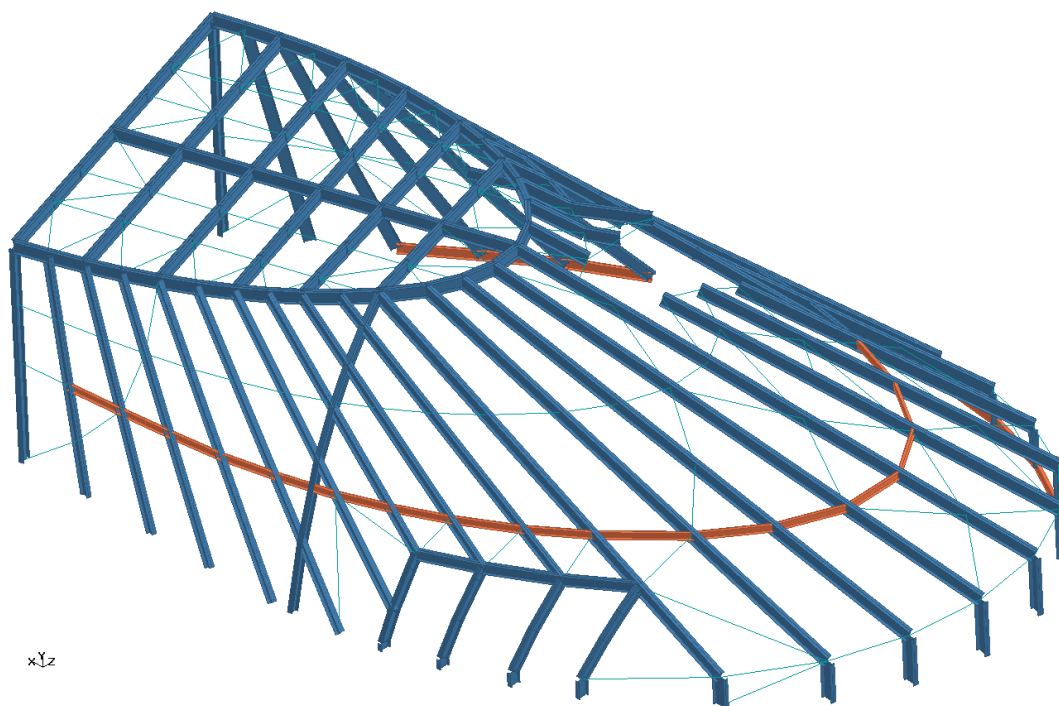
**Figure 5.9** Three separate elements from the Revit add-on tool.



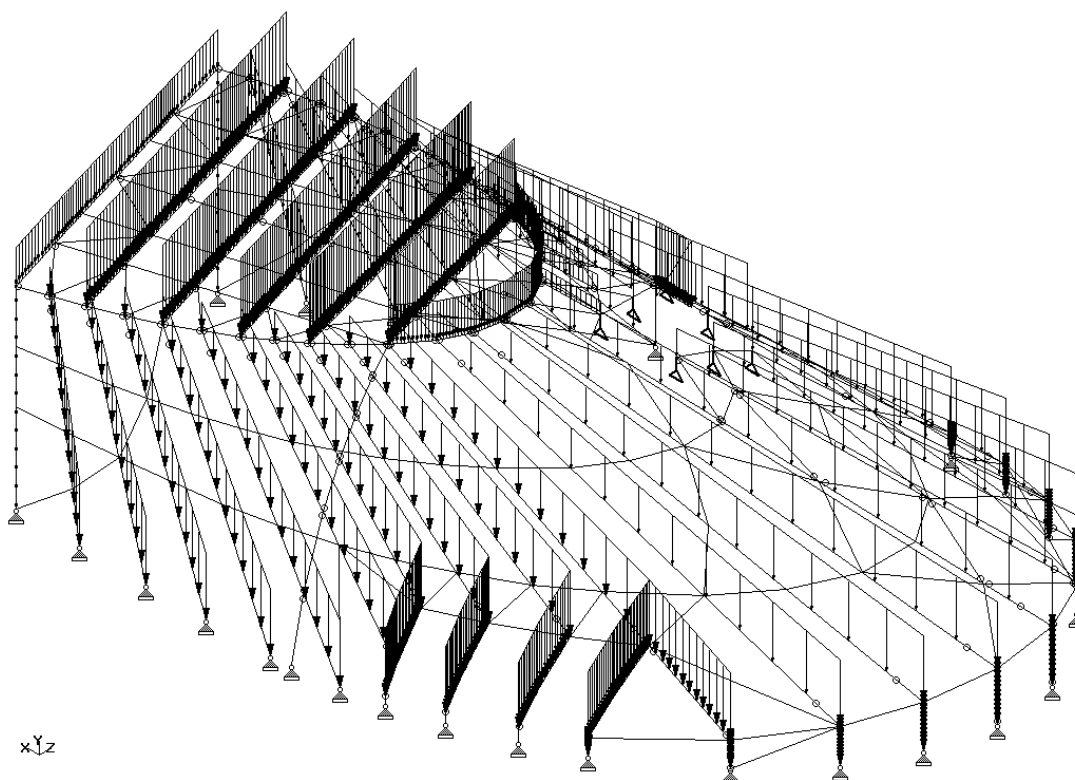
**Figure 5.10** Statical system and line loads in Robot.

After using the direct link to StaadPro the steel structure appears as shown in Figure 5.11 in 3D rendering before any corrections are made. The statical system and line loads appear as shown in Figure 5.12 after correction of boundary conditions, releases and loads.





**Figure 5.11** *The IPE and UNP profiles in StaadPro.*



**Figure 5.12** *Static system and line loads in StaadPro.*

As described previously the models in Robot and StaadPro are based on the analytical model in Revit and there might be some difference between the physical model here and in Revit.

|                                   | RVT | RVT<br>add-on   | RVT<br>↓<br>RSA | RVT<br>↑<br>RSA | RVT<br>↓<br>SPro | RVT<br>↑<br>SPro |
|-----------------------------------|-----|-----------------|-----------------|-----------------|------------------|------------------|
| <b>1. Section properties</b>      |     |                 |                 |                 |                  |                  |
| Section class                     | ÷   | ÷               | ✓ <sup>2</sup>  | 1               | ✓                | 1                |
| Height $h$                        | ✓   | ÷               | ✓               | ✓               | ✓                | ✓                |
| Width $b$                         | ✓   | ÷               | ✓               | ✓               | ✓                | ✓                |
| Web thickness $t_w$               | ✓   | ÷               | ✓               | ✓               | ✓                | ✓                |
| Flange thickness $t_f$            | ✓   | ÷               | ✓               | ✓               | ✓                | ✓                |
| Radius $r$                        | ✓   | ÷               | ÷               | ✓               | ÷                | ✓                |
| Area $A$                          | ✓   | ✓               | ✓               | ✓               | ✓                | ✓                |
| Moment of inertia $I_y$           | ÷   | ✓ <sup>3</sup>  | ✓               | 1               | ✓                | 1                |
| Moment of inertia $I_z$           | ÷   | ÷               | ✓               | 1               | ✓                | 1                |
| Torsion constant $I_t$            | ÷   | ÷               | ÷               | 1               | ÷                | 1                |
| Warping constant $I_w$            | ÷   | ÷               | ÷               | 1               | ÷                | 1                |
| Plastic modulus $W_{pl,y}$        | ÷   | ÷               | ÷               | 1               | ✓                | 1                |
| Plastic modulus $W_{pl,z}$        | ÷   | ÷               | ÷               | 1               | ✓                | 1                |
| <b>2. Geometry</b>                |     |                 |                 |                 |                  |                  |
| Length $l$                        | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| Effective length $l_{eff}$        | ÷   | ÷               | ✓ <sup>4</sup>  | 1               | ✓ <sup>4</sup>   | 1                |
| <b>3. Material properties</b>     |     |                 |                 |                 |                  |                  |
| Yield stress $f_y$                | ✓   | ÷               | ✓               | ÷               | ÷ <sup>5</sup>   | ÷                |
| Modulus of elasticity $E$         | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| Shear modulus $G$                 | ✓   | ÷               | ✓               | ÷               | ✓                | ÷                |
| Density $\rho$                    | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| <b>4. Loads</b>                   |     |                 |                 |                 |                  |                  |
| Magnitude $g, s$                  | ✓   | ÷ <sup>6</sup>  | ✓               | ÷               | ✓ <sup>7</sup>   | ÷                |
| Position                          | ✓   | ÷ <sup>6</sup>  | ✓               | ÷               | ✓ <sup>8</sup>   | ÷                |
| Combination                       | ✓   | ✓               | ✓               | ÷               | ✓                | ÷                |
| <b>5. Boundary conditions</b>     |     |                 |                 |                 |                  |                  |
| Roller                            | ✓   | ✓ <sup>9</sup>  | ✓               | ÷               | ÷ <sup>10</sup>  | ÷                |
| Pinned                            | ✓   | ✓ <sup>9</sup>  | ✓               | ÷               | ✓                | ÷                |
| Releases                          | ✓   | ÷               | ✓               | ÷               | ÷ <sup>11</sup>  | ÷                |
| <b>6. Design data</b>             |     |                 |                 |                 |                  |                  |
| Moment capacity $M_{pl,R}$        | ÷   | ÷               | ✓               | 1               | ✓                | 1                |
| Reduced moment capacity $M_{N,R}$ | ÷   | ÷               | ✓               | 1               | ✓                | 1                |
| Shear capacity $V_{c,R}$          | ÷   | ÷               | ✓               | 1               | ✓                | 1                |
| Shear capacity $V_{T,R}$          | ÷   | ÷               | ✓               | 1               | ✓                | 1                |
| Normal capacity $N_{pl,R}$        | ÷   | ÷               | ✓               | 1               | ✓                | 1                |
| Normal capacity $N_{cr}$          | ÷   | ÷               | ÷               | 1               | ÷                | 1                |
| <b>7. Results</b>                 |     |                 |                 |                 |                  |                  |
| Deflection                        | ÷   | ÷ <sup>12</sup> | ✓ <sup>13</sup> | 1               | ÷                | 1                |
| Section forces                    | ÷   | ÷ <sup>12</sup> | ✓ <sup>13</sup> | 1               | ÷                | 1                |
| EC3 6.2.5                         | ÷   | ÷               | ✓ <sup>13</sup> | 1               | ÷                | 1                |
| EC3 6.2.6 (Z)                     | ÷   | ÷               | ✓ <sup>13</sup> | 1               | ÷                | 1                |
| EC3 6.2.6-7                       | ÷   | ÷               | ✓ <sup>13</sup> | 1               | ÷                | 1                |
| EC3 6.3.3                         | ÷   | ÷               | ✓ <sup>13</sup> | 1               | ÷                | 1                |

**Table 5.2** Test results for three-dimensional steel structure. ✓ means no problems and ÷ means that it does not work or that the parameter/feature is not available.

Notes to Table 5.2:

- 1) This parameter is not available in Revit.
- 2) The connections are not transferred correct from Revit. This causes a different statical system. Thus the section forces are different from the section forces in the original model. The changed section forces cause that Robot chooses another section class for the profiles than in the original model.
- 3) For the slanted beams and columns the moment of inertia are defined according to the angle of the beams and columns. For elements that are not parallel to the global coordinate system the moment of inertia is wrong.
- 4) The effective length is equal to the length of the elements. This is not necessarily correct but maintained since it is default in Robot and StaadPro. Furthermore it is not relevant for the tests.
- 5) By default set to 235 MPa in StaadPro. Must be defined manually if different from this value.
- 6) The add-on tool does not register the loads transferred from adjacent elements. This means that only the loads added directly to the elements are used.
- 7) Loads are missing for three elements.
- 8) For some of the elements the load is positioned outside the element. The error is small and can be caused by rounding errors. It has no influence on the results.
- 9) The add-on tool registers all node points along the elements, where other elements intersect. Pinned supports are automatically added by the add-on tool to these intersection nodes. These must be manually deleted. The original supports are handled correct.
- 10) The degrees of freedom should be *ffxfff* in Revit coordinates corresponding to *fxffff* in StaadPro coordinates but the degrees of freedom are *ffxfff* in StaadPro coordinates.
- 11) All releases are wrong due to the different orientation of the coordinate system in Revit and StaadPro.
- 12) The results are wrong since not all of the loads are taken into account cf. note 6.
- 13) The results are calculated but they are not correct according to the errors in the model cf. note 2.

As shown in Figure 5.11 only IPE and UNP profiles are exchanged to StaadPro. I.e. SHS profiles are not transferred, and must be redefined manually, which is easily done. In StaadPro there is another error, namely that infinite deformations occur in a few elements even though the boundary conditions and releases are redefined as described in Appendix G.3. The reason for this is unknown.

The results from Robot and StaadPro after import from Revit are not consistent, neither with each other, nor with the results from the original Robot model. Since the releases seem to be wrong, they are all removed and the results are compared again. Still the three models are not consistent. This can be due to the following:



- The rotation of the profiles is not correct in StaadPro.
- For somewhat reason the connections are not transferred correct from Revit to Robot in the sense that some extra nodes are added in some of the connections. This causes a different statical system.
- The cross sections are not defined in the same manner in Robot and StaadPro. This was not previously an issue.

The influence of the occurred errors has not been investigated further.

It should be noticed that the code check in Robot is made in a common point for each element, where StaadPro makes the code check in a critical section for each design criterion. Further StaadPro checks more design criteria than Robot. However this has nothing to do with the linking between Revit and the two applications. Therefore it does not appear from Table 5.2.

## 5.5 Evaluation of tests

Based on the results presented in Table 5.2 an evaluation of the applicability of the S-BIM tools in relation to the steel structure is made.

### Revit add-on tool (RVT add-on)

☆☆☆☆

The Revit add-on tool gets no stars because it is not possible to compute neither the deflection nor the section forces correct. This is mainly due to the fact that the reactions from the adjacent elements are not added as loads to the element in question. Furthermore it is not possible to assess the design criteria.

### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

★★☆☆

In this test the direct link gets two stars because it is possible to exchange almost all relevant data from Revit to Robot. However there is something wrong with the node points or connections. This means that the statical system for the entire structure is different from the original model. Only the cross section can be updated correct backwards from Robot to Revit.

### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

★★☆☆

The link gets two stars since it is useful in relation to transfer geometry, material properties and loads from Revit to StaadPro. Different orientation of the coordinate system (both global and local) in Revit and StaadPro causes boundary conditions and releases to be reversed. Some cross sections must be defined manually when exchanging from Revit to StaadPro. If this is done, StaadPro checks almost the same design criteria as Robot. Only some of the section properties are updated backwards from StaadPro to Revit.

### 5.6 Subconclusion

In this chapter a three-dimensional steel structure from the House of Music in Aalborg has formed the basis of the evaluation of the applicabilities of the tested S-BIM tools.

The structure was chosen to see if the S-BIM tools can handle a structure which is more advanced than the structures in Chapter 3 and 4. The structure is more advanced in the sense that it consists of several elements, that the elements are joint together in three dimensions and that the overall form of the structure does not follow any traditional geometric shape.

The three-dimensional steel structure was originally modelled by Rambøll in Tekla. In stead of modelling the structure from the bottom in Revit it has been imported via the DWG, IFC and CIS/2 file formats. However none of the models gave a satisfactory representation of the three-dimensional steel structure in Revit.

As an alternative the three-dimensional steel structure was imported to Revit via CIS/2 from Robot to obtain a complete model. Since loads and boundary conditions were not transferred with the CIS/2 file format, these have to be modelled manually in Revit. Also some corrections have to be made manually in Revit. In that connection it should be noticed that Revit is not suitable for modelling elements which are not horizontal or elements which are not parallel to the global axes.

#### **Revit add-on tool (RVT add-on)**

The Revit add-on tool is not suitable for three-dimensional structures since loads from adjacent elements are not taken into account when analysing a single element. However this should be improved in the next release of Revit, *Autodesk Revit Structure 2011*, which have an add-on for load take-down.

#### **Direct link from Revit to Robot and backwards (RVT ↔ RSA)**

This direct link makes it possible to evaluate the three-dimensional steel structure according to Eurocode 3. However the modelling problems in Revit influence the statical system in Robot. A common node where several elements are joined in Revit are split up into several nodes when exported to Robot. Therefore special attention has to be paid to the connections of the steel structure. It is only possible to update the cross section from Robot to Revit.

#### **Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)**

This direct link is useful in relation to geometry, material properties and loads. However the *SI Xchange* link does not currently support custom steel sizes. Thus it has not been possible to exchange all elements of the 3D steel structure. As described the orientation of the coordinate system causes boundary conditions and releases to be reversed<sup>1</sup>. Despite of the errors obtained the link is considered almost as good as the link to Robot, since the errors are easily corrected when they are known.

It is difficult to determine which of the direct links is best in these tests, since it is not clear what causes the errors in the models. Further neither of the results is consistent with the results of the original model nor with each other.

Based on all the tests in the previously chapters it is still the direct link between Revit and Robot which seems to be best. However the tests performed with the three-dimensional steel structure show that none of the tested S-BIM tools are currently capable of handling structures with a certain degree of complexity.

---

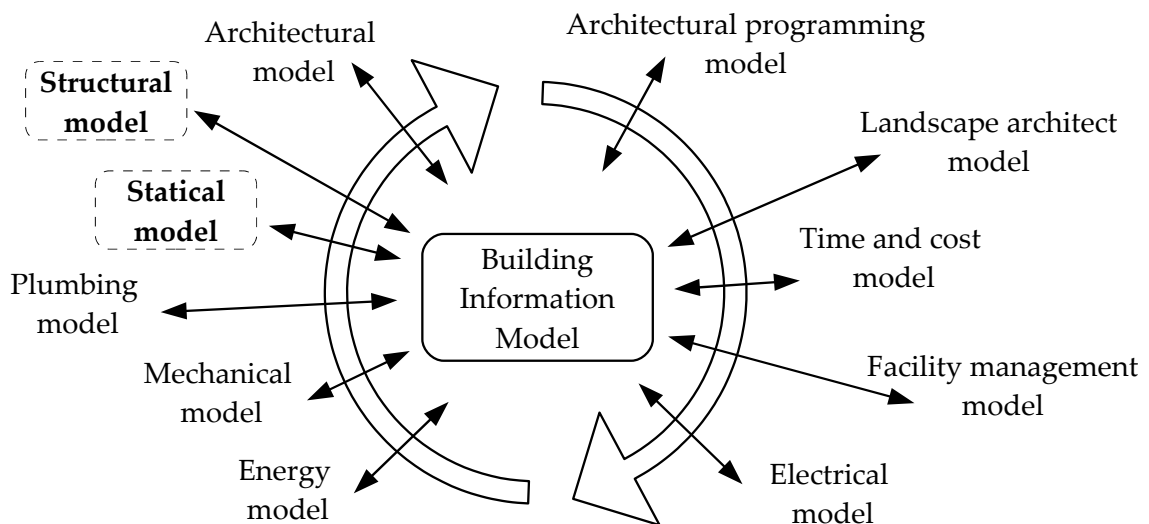
<sup>1</sup>This issue should have been resolved in the current version (v1.0.5.2010) according to the ReadMe file: In some cases, end releases of members were reversed in STAAD. This has been resolved [Structural Integrators, 2009].

## Discussion

In this chapter the contents presented in the previous chapters are discussed. BIM as a vision and the applicabilities of current S-BIM tools are discussed. Further an evaluation of which technology is most preferable for the future is given.

### 6.1 BIM as a vision

In "BIM as a vision" proposed by Coenders [2009], the BIM (model) forms the basis for digital, virtual and computational models. As described in Chapter 2 the BIM (model) includes a lot of information e.g. input for calculations, basis for drawings, cost estimates, visualisation and time schedules. Some of the information are tree-dimensional models. Other parts of the information are text and diagrams. I.e. the BIM (model) consists of much more than just three-dimensional models. An example of a BIM (model) with different sub-models is shown in Figure 6.1.



**Figure 6.1** The BIM (model) containing several sub-models.

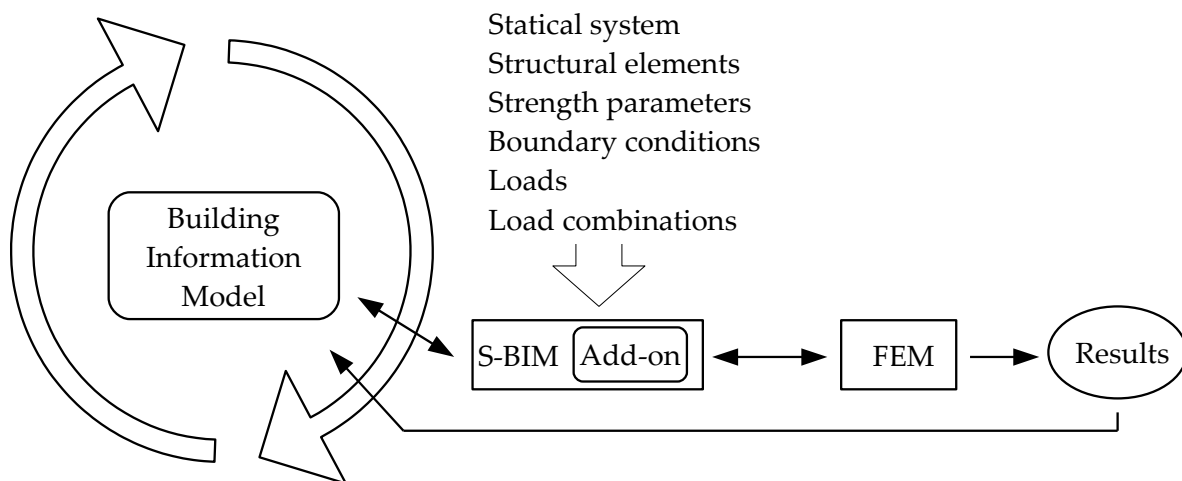
The information included in the BIM (model) is produced continually by the different participants in the building process. Thus the BIM (model) is relevant through the entire process, starting with the program phase and ending with demolition after the operation phase.

## 6. Discussion

This study has focused on the structural engineering part in the detail design phase of the building process. Thus the structural model and the statical model highlighted in Figure 6.1 have been in focus.

In theory BIM enables a continuous workflow where the needed information is constantly available for all the participants. This eliminates the need to recreate data models. For instance the architectural model can be based on the model by the landscape architect. Further e.g. the energy model, the electrical model and the structural model can be based on the architectural model. Thus the data model created by the architect can form the basis for the structural engineering model – the S-BIM (model).

In order to obtain a continuous workflow in the structural design phase the architectural components must be converted to structural elements. Following boundary conditions, structural material properties, loads and load combinations are added in the S-BIM software application. The S-BIM (model) now includes all the needed information in order to perform a structural analysis and assess the criteria in the Eurocodes via a FEM application. This continuous workflow is shown in Figure 6.2.



**Figure 6.2** Continuous workflow from the BIM (model) to the results of calculations in the structural design phase.

Hence, from the beginning of this project, the vision for the structural design phase was a process where the need for remodelling is reduced to a minimum. The expectations to the results of the performed tests have been based on this vision.

## 6.2 Applicabilities of current S-BIM tools

Based on the vision for the structural design phase, the Revit add-on tool has been tested. Furthermore, the data exchange between the S-BIM software Revit and the FEM software Robot and StaadPro have been tested. To give an overview, the evaluations from the previous chapters are presented in Table 6.1.

|                        | RVT add-on | RVT ↔ RSA | RVT ↔ SPro | RVT $\xrightarrow{\text{IFC}}$ RSA |
|------------------------|------------|-----------|------------|------------------------------------|
| Simple steel beam      | ★ ☆ ☆ ☆ ☆  | ★ ★ ★ ★ ☆ | ★ ★ ★ ★ ☆  | ☆ ☆ ☆ ☆ ☆                          |
| Simple timber column   | ☆ ☆ ☆ ☆ ☆  | ★ ★ ★ ☆ ☆ | ★ ★ ☆ ☆ ☆  | ☆ ☆ ☆ ☆ ☆                          |
| Simple concrete beam   | ★ ☆ ☆ ☆ ☆  | ★ ☆ ☆ ☆ ☆ | ★ ☆ ☆ ☆ ☆  | ☆ ☆ ☆ ☆ ☆                          |
| Timber frame structure | ★ ☆ ☆ ☆ ☆  | ★ ★ ★ ☆ ☆ | ★ ★ ☆ ☆ ☆  | -                                  |
| 3D steel structure     | ☆ ☆ ☆ ☆ ☆  | ★ ★ ☆ ☆ ☆ | ★ ★ ☆ ☆ ☆  | -                                  |

Table 6.1 Overview of the results of the performed tests.

In the following, the contents of Table 6.1 will be discussed.

### 6.2.1 Add-on tool for S-BIM software

In general, the Revit add-on tool *Revit Extensions, Simulation - Static Analysis of Frames* is capable of calculating section forces and deflection. For somewhat reason it has not been possible to get correct results in connection with the timber column. This is rather strange, since the other simple structures, and the timber frame structure did not cause this issue.

In general, no assessment of the design criteria, given in the Eurocodes, is possible in the employed Revit add-on tool. Thus the Revit add-on tool did not live up to the initial vision, but maybe this was never the intention. However, the Revit add-on tool can be rather useful for feasibility studies if a 'load-takedown' feature is introduced. Otherwise it is only useful for very simple structures.

### 6.2.2 Direct link

The direct links from Revit to Robot and StaadPro, respectively give the best results of data exchange between the applications. However none of the links work as fully developed two-way links.

The link between Revit and Robot *Integration with Robot Structural Analysis* and the link between Revit and StaadPro *SI Xchange* are almost equally capable of handling steel structures. For the simple beam they both work well from Revit to Robot and StaadPro respectively, but it is only possible to update section properties backwards. For the three-dimensional steel structure neither the *Integration with Robot Structural Analysis* link nor the *SI Xchange* link work without problems.

The two links are also equal in connection with the general procedure of the concrete structures since none of them can handle reinforcement. However an alternative link between Revit and Robot *Reinforcement Design* enables data exchange between the two applications. A similar link is not available between Revit and StaadPro.

In connection with timber structures the link *Integration with Robot Structural Analysis* is better than the *SI Xchange* link. This applies to both export of information from Revit and import of information to Revit. However, the *SI Xchange* link is only intended for steel and concrete, cf.

Appendix B.1, which explains the limited applicability of handling timber structures.

Recently, Jardim-Goncalves and Grilo [2010] stated that:

*Software companies are now developing suites of modeling and construction-related software tools that are interoperable, but they tend only to address interoperability among themselves and not in relation to other vendors' applications.*

[Jardim-Goncalves and Grilo, 2010, p. 387]

Thus it was expected that the interoperability between Revit and Robot would be superior to the interoperability between Revit and StaadPro. However, this was in general not the case. In principle, the only difference between the two links is that StaadPro uses a different coordinate system than Revit and Robot. This issue is not handled very well by the *SI Xchange* link, but is quite easily corrected in StaadPro.

In connection with the handling of structures in steel, timber and reinforced concrete it should also be noticed that steel is the simplest material to model since it is isotropic. Also it should be noticed that Robot and StaadPro originally are developed for steel structures. This might also be the case for the links to the applications. Therefore it is not surprising that the best results are obtained with the simple steel structure. However the tests show that none of the tested S-BIM tools are currently capable of handling structures with a certain degree of complexity.

Even though the results of the data exchange, to some extent, are in accordance with the expectations they do not live up to the vision for data exchange in the structural design phase. I.e. the direct links do not enable a continuous workflow, from the S-BIM (model) to the results of calculations, where remodelling is unnecessary.

A disadvantage of the direct links is the need for many different links, since there are several different S-BIM software applications and several different FEM software applications from different software vendors, which all needs to be mutual compatible.

### 6.2.3 Indirect link

The indirect linking in this project has been from Revit to Robot via the IFC file format. The data exchange via IFC was rather incomplete since only information about geometry and to some extent section properties were transferred.

The IFC Coordination View is not suitable for data exchange between S-BIM and FEM software applications. This was never the intention, since the IFC Structural Analysis View is available for this job. However Revit and Robot only support the IFC Coordination View. Therefore the results of the data exchange are in accordance with the expectations.

In the assessment of IFC it should be noticed that structural engineering was first integrated in IFC2x2 cf. Section 2.2. Therefore the IFC file format might not be fully developed in accordance with e.g. the Structural Analysis View and some of the possibilities might be further developed in future releases. This might also be the reason for why the IFC Structural Analysis View is not yet supported in the current version of Revit Structure (2010). Otherwise this would be an obvious choice.

The limitations in the applied applications make it difficult to evaluate the applicability of IFC with regards to the data exchange in the structural design phase.

However there exist other software applications in which the IFC Structural Analysis View is implemented. An example of this is Tekla Structures. In Hejnfelt and Øksengaard [2007] export of information via a structural IFC file from Tekla Structures was tested. The result was not successful. According to Ville Rousu, Tekla Corporation, introducing any new standard takes time [Hejnfelt and Øksengaard, 2007]:

*The Coordination View of IFC has been there for five years and is finally breaking through. Therefore he (Editor's note: Ville Rousu) thinks it will still take some time before the structural view of IFC will work properly.*

[Hejnfelt and Øksengaard, 2007, p. 41]

Even though the result obtained by use of IFC is incomplete, this method might be the best if the software applications support the relevant views of the format. This is due to the independence of the file format. Hejnfelt and Øksengaard [2007] asked Kjeld Svidt, Aalborg University, why IFC is better than the direct links:

*Say there are 10 different CAD applications and 50 different applications to link to. All the combinations have to be considered and using only direct links there will simply be too many combinations. With a standard format like IFC, the applications only have to be able to read and write to one single format.*

[Hejnfelt and Øksengaard, 2007, p. 41]

The presented comments from Hejnfelt and Øksengaard [2007] are in accordance with the assessment of IFC in this study.

Another advantage of IFC is the possibility for 'clash' control. As previously described, the BIM (model) consists of a number of sub-models produced by different participants in the building process. The sub-models shown in Figure 6.1 can be created in a lot of different software applications. To reduce design errors, it can be very useful if all the models are saved as IFC files which can be imported in e.g. *Solibri Model Checker* [Solibri, 2010].

This was for instance experienced during *The Digital Days*<sup>1</sup> (in Danish: De Digitale Dage) which the authors attended in April, 2010. Here architects, engineers within different disciplines, draughtsmen, and craftsmen worked on a building design for three days. During this process, clashes between the plumbing model and the structural model among other things were detected by means of *Solibri Model Checker*.

### 6.2.4 New software versions

The above-mentioned assessment of the applicability of the S-BIM tools are based on the software applications presented in Section 2.5. For some of the applications newer versions are on their way or already released. For instance *Autodesk Revit Structure 2011* and *Autodesk Robot Structural Analysis Professional 2011* both have been released this spring whereas IFC 2x4 will be released later this year. Also the *SI Xchange* link is being updated cf. Appendix B.1.

Some of the issues observed during this study might be solved in these new releases. In spite of this, further development is necessary for all of the S-BIM tools.

<sup>1</sup>The Digital Days is a cooperation between four educational institutions in North Jutland within construction. The aim of the concept is to develop and disseminate knowledge about Digital Construction [De Digitale Dage, 2010].

### 6.3 Which technology is most preferable for the future?

Regarding the main focus of this study it was found that the direct links from the S-BIM software to FEM applications – compared to the add-on tool in Revit and the indirect link – are the most optimal way to assess the design criteria in the Eurocodes at the moment.

This is mainly due to the fact that the add-on tool does not enable design by Eurocodes, and the fact that neither of the tested software applications supports the IFC Structural Analysis View.

*But is the direct links the way to go in the future?*

The authors would not recommend this solution, because it would demand many different links, since there are several different S-BIM software applications and several different FEM software applications from different software vendors, which all needs to be mutual compatible.

The Revit add-on tool is, at the moment, only useful for a quick feasibility study, if a 'load takedown' feature is available. If assessment of the design criteria from Eurocodes should be possible, in fact several FEM applications need to be implemented in the S-BIM applications. This would result in huge and complex software applications where the users would be dependant of a single software vendor.

A more feasible solution would be to make the different software applications compatible with a single common neutral file format, like the IFC Structural Analysis View. This enables the use of several different software applications from different software vendors.

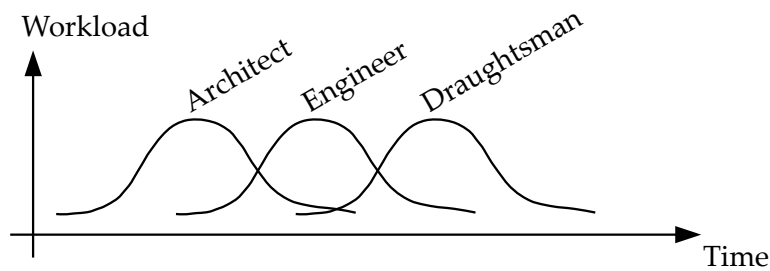
### 6.4 Which process is most preferable for the future?

The initial vision of BIM presented in Section 6.1 has the continuous workflow in focus where the architectural model can be converted to a structural model ready for structural analysis. This has only briefly been treated in this study in Chapter 5. Here it was found that the tested methods did not enable a continuous workflow from the model original made in Tekla to the S-BIM (model) in Revit. In fact remodelling the entire structure in Revit was necessary.

*But is the continuous workflow the most preferable for the future?*

In a traditional structural design phase the participants work on separate models. For instance the architect is far in his or hers work before the information are passed on to other participants. When the structural engineer has received enough information from the architect, he or she creates a new model. The calculations are based on this model. Later, when enough information is available for the draughtsman, he or she creates yet another model. This model is not linked to the engineering model, but sets of in it. The model, created by the draughtsman, forms the basis of drawings. I.e. the architect, the engineer and the draughtsman work on separate models staggered in time. The current workflow was presented in Section 1.1, and is shown in Figure 6.3.





**Figure 6.3** Traditional workflow, where the workloads are staggered in time.

As described previously, a workflow like the one shown in Figure 6.3 might not be the most effective. Therefore a more continuous workflow, as shown in Figure 6.2, was suggested. Cf. Section 2.1.1, this was also suggested by two of the engineers referred to in Hejnfelt and Øksengaard [2007]:

*In principle it would be ingenious if the engineer could get data directly from the architect and send it directly to the contractor and so on... Exchange of data should be as automated as possible without loss of quality.*

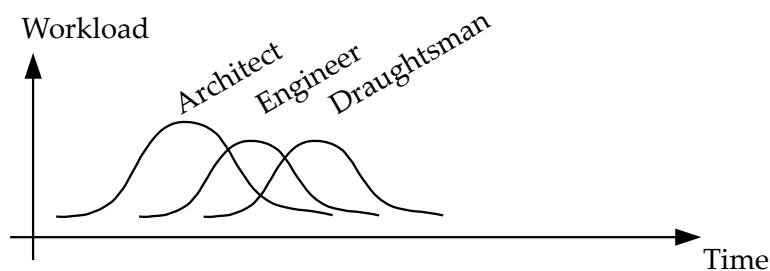
[Hejnfelt and Øksengaard, 2007, Appx A]

However, a continuous workflow demands a lot of information in the beginning of the process. Further, a continuous workflow demands that the links between the BIM (model) and the S-BIM (model) as well as between the S-BIM (model) and the calculation software work properly, both forwards and backwards.

It is not likely, that all the information needed for structural analysis is available in the beginning of the process. Nor is the information within the other disciplines of engineering available. Further, an integrated process, like the one suggested, can cause some problems in connection to which participants are responsible for possible design errors.

Therefore separate models might still be the most preferable workflow in the future. But instead of starting from ground zero both the structural engineer and the draughtsman can set off in the BIM (model) containing the architect model among other things. This could be done by use of a common neutral file format which also can be used for coordination and 'clash' control during the design process.

By setting off in the BIM (model), the time needed in the design phase, and the workload of the engineer and draughtsman are reduced. Both benefits are illustrated in Figure 6.4.



**Figure 6.4** Workflow employing BIM.

With a workflow like the one shown in Figure 6.4 the workload is staggered from right to the left. This is beneficial since possible changes of design can be implemented earlier in the

building process, which is beneficial since the cost of changes in the design increases during the building process.

To secure the information flow during the building process as shown in Figure 1.3, it should be possible to 'map' the architectural elements to structural elements. This feature is in fact already available, as a copy/monitor function, when importing a Revit Architecture model in Revit Structure [Weir et al., 2009]. This has not been tested in this study, but the feature was briefly introduced during *The Digital Days*.

By using S-BIM, as suggested above, the time needed in the structural design phase, and the workload of the engineer and draughtsman are reduced. There might be similar benefits of using BIM in the other disciplines of engineering. Further, working of different models keep the division of responsibilities clear while the possibility of e.g. 'clash' control is maintained.

## Conclusion

In the following a brief summary of the previous chapters is given.

### Chapter 1

The first chapter gives an introduction to the building process and some of the benefits of employing BIM.

### Chapter 2

The second chapter introduces the relevant BIM aspects, e.g. IFC and CIS/2. Furthermore Structural Building Information Modelling (S-BIM) and the employed S-BIM tools are introduced. The S-BIM tools tested are: Revit add-on tool, direct links between Revit and Robot or StaadPro, and indirect linking between Revit and Robot via IFC. Finally the scope of the project and the general methods employed are presented.

### Chapter 3

The third chapter gives an initial evaluation of the S-BIM tools which are tested through three rather simple structures with different section properties, geometry, material properties and so on. Based on the tests performed in this chapter it is concluded that the direct link *Integration with Robot Structural Analysis* is most preferable. It is found that the Revit add-on tool is only capable of calculating section forces and deflections. The indirect IFC-link is found rather useless since Revit and Robot does not support IFC Structural Analysis View but only the IFC Coordination View. Thus IFC is not tested further. Furthermore it is found that neither of the S-BIM tools were able to handle reinforced concrete, since it is not possible to transfer reinforcement from Revit to any of the calculation software tested.

### Chapter 4

The fourth chapter presents the applicability of the S-BIM tools when analysing a timber frame structure, which is more advanced than the simple structures in Chapter 3. The structure is more advanced in the sense that several elements are joint together, that neither of the elements are vertical nor horizontal, and several of the beams are tapered with varying section height. Neither of the S-BIM tools supports tapered beams. Thus the tapered beams were modelled as pieces of beams with constant rectangular cross section. The Revit add-on tool is still only capable of calculating section forces and deflection. It is found that the link *Integration with Robot Structural Analysis* is better than the *SI Xchange* link.

### Chapter 5

The fifth chapter includes the step before the data exchange between the S-BIM software and the FEM software. I.e. the data transfer to the S-BIM software. The structure in question has been modelled by Rambøll in Tekla Structures. Use has been made of the file formats DWG, IFC and CIS/2. None of the three file formats gives a satisfactory representation of the three-dimensional steel structure after import to Revit. As an alternative the structure was imported to Revit via CIS/2 from Robot to obtain a complete model.

The three-dimensional steel structure is more advanced than the previous structures, in the sense that it consists of several elements, that the elements are joint together in three dimen-

sions and that the overall form of the structure does not follow any traditional geometric shape.

It is found that the Revit add-on tool is not suitable for three-dimensional structures since loads from adjacent elements are not taken into account when analysing a single element. In general the S-BIM tools did not provide consistent results. Neither the *Integration with Robot Structural Analysis* link nor the *SI Xchange* link work without problems. For somewhat reason the connections are not transferred correct from Revit to Robot in the sense that some extra nodes are added in some of the connections. Different orientation of the coordinate system in Revit and StaadPro causes boundary conditions and releases to be reversed. Both cause a different statical system than intended.

### Chapter 6

The sixth chapter discusses the contents presented in the previous chapters. BIM as a vision and the applicabilities of current S-BIM tools are discussed. Further an evaluation of which technology is most preferable for the future is given.

After summing up the contents and sub conclusions of the previous chapters, the questions from the thesis statement can be answered. The thesis statement was:

*“What are the strengths and limitations in the current (a) add-on BIM tools, (b) direct links between S-BIM and FEM applications, and (c) IFC exchange file format, and which technology is most preferable for the future?”*

Re (a) The tested Revit add-on tool can be rather useful for calculating section forces and deflection in feasibility studies if a ‘load-takedown’ feature is introduced. But to assess the criteria in Eurocodes a separate application is needed.

At current, the Revit add-on tool can not – and should not – replace the traditional FEM software applications since the applicability of this tool is rather limited.

Re (b) The direct links between Revit and Robot or StaadPro are useful for steel structures of limited complexity. However, none of the direct links can handle reinforced concrete satisfactorily. Regarding timber structures, the direct link *Integration with Robot Structural Analysis* is better than the direct link *SI Xchange* since this link does not support timber materials. Due to this limitation, the direct link between Revit and Robot is most preferable at present.

Re (c) The IFC Coordination View was not found suitable for data exchange between S-BIM and FEM software applications. However, this was never the intention since the IFC Structural Analysis View was developed for this.

None of the tested software applications support IFC Structural Analysis View which makes them unsuitable for data exchange via the IFC file format.

According to the above-mentioned conclusions it is found that the current software applications are too simplistic. This is in agreement with the statement by Coenders [2009] regarding “BIM as a software technology”.

Even though it is found that the direct links work best, it is questioned whether this is the way to go in the future. The authors instead recommend that the structural software applications integrate the IFC Structural Analysis View. This enables the use of several different software applications from different software vendors. In this way, the structural engineer is free to choose specific FEM software applications for specific purposes, and is less dependant of a single software application.

---

It should be noticed that the S-BIM tools tested in this study only represent a small part of the S-BIM tools available. For instance there exist a number of extensions in Revit. Furthermore there exist several additional S-BIM software applications and FEM software applications. These tools might be better than the S-BIM tools tested in this study. Therefore, it would be interesting to test more S-BIM tools as well as the new versions of the already tested S-BIM tools. This could be a subject for further investigation.

Even though it has been found that S-BIM, at the moment, might not be fully developed and that the continuous workflow might not be the most preferable for the future, BIM still is an important part of the future building process. This is due to the fact that the structural part of BIM still is a relatively new upcoming technology which needs further development, whereas other parts of BIM already might be integrated.



# Bibliography

- Autodesk. *Autodesk Revit Structure*, 2010a. URL <http://www.autodesk.dk/revitstructure>. 2010.06.08.
- Autodesk. *Autodesk Robot Structural Analysis Professional*, 2010b. URL <http://www.autodesk.co.uk/robot>. 2010.06.08.
- Autodesk. *Revit Extensions for Autodesk Revit Structure 2010*, 2010c. URL <http://www.extensions4revit.com>. 2010.06.08.
- E. Bejder and W. Olsen. *Anlægsteknik 2, Styring af byggeprocessen*. Polyteknisk Forlag, 2005. ISBN 978-87-502-0966-9.
- K. Bell. *Vurdering av skader på limtredragere i Krafthallen (Tromsø), med hovedvekt på den statiske bære virkning*. Institutt for konstruksjonsteknikk, NTNU, 2005.
- Bentley. *StaadPro v8i*, 2008. URL <http://www.bentley.com/da-DK/Products/STAAD.Pro/>. 2010.06.08.
- bips. *3D arbejdsmetode 2006*. bips, 2006. ISBN 87-91340-55-1.
- BS EN 1993-1-1:2005. *Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings*. The British Standards Institution, 2005.
- buildingSMART. *Model - Industry Foundation Classes (IFC)*, 2010a. URL <http://www.buildingsmart.com/bim>. 2010.06.08.
- buildingSMART. *General questions about buildingSMART, IAI, and IFC*, 2010b. URL <http://www.iai-tech.org/services/faq/faq-general-questions>. 2010.06.08.
- buildingSMART. *What's new in IFC2x4*, 2010c. URL [http://www.iai-tech.org/ifc/IFC2x4/rc1/html/change/IFC2x4-rc1\\_whats\\_new.htm](http://www.iai-tech.org/ifc/IFC2x4/rc1/html/change/IFC2x4-rc1_whats_new.htm). 2010.06.08.
- buildingSMART. *IFC Extension Projects - Completed projects*, 2010d. URL [http://www.iai-tech.org/projects/ifc\\_extension\\_projects/completed](http://www.iai-tech.org/projects/ifc_extension_projects/completed). 2010.06.08.
- buildingSMART. *IFC Extension Projects - Current projects*, 2010e. URL [http://www.iai-tech.org/projects/ifc\\_extension\\_projects/current](http://www.iai-tech.org/projects/ifc_extension_projects/current). 2010.06.08.
- buildingSMART. *Summary of IFC Releases*, 2010f. URL [http://www.iai-tech.org/products/ifc\\_specification/ifc-releases](http://www.iai-tech.org/products/ifc_specification/ifc-releases). 2010.06.08.
- CIMsteel. *CIS/2.0*, 2003. URL <http://www.cis2.org/index-bak.htm>. 2010.06.08.
- E. F. Codd. A relational model of data for large shared data banks. *Commun. ACM*, 13(6): 377–387, 1970.

- J. L. Coenders. Parametric and associative design as a strategy for conceptual design and delivery to BIM. *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia*, pages 1112–1123, 2009.
- CoopHimmelB(l)au. *House of Music*, 2010. URL <http://www.coop-himmelblau.at>. 2010.06.08.
- De Digitale Dage. *De digitale dage på UCN*, 2010. URL <http://www.dedigitaledge.dk>. 2010.06.08.
- Det Digitale Byggeri. *Bygherrekravene*, 2010a. URL [http://www.detdigitalebyggeri.dk/public\\_client/bygherrekravene](http://www.detdigitalebyggeri.dk/public_client/bygherrekravene). 2010.06.08.
- Det Digitale Byggeri. *IFC – IFC-modeller*, 2010b. URL <http://www.detdigitalebyggeri.dk/tech-article/ifc-%E2%80%93-ifc-modeller>. 2010.06.08.
- dev.ifd-library.org. *The three pillars of buildingSMART*, 2007. URL [http://dev.ifd-library.org/index.php/Ifd:buildingSMART\\_and\\_IFD](http://dev.ifd-library.org/index.php/Ifd:buildingSMART_and_IFD). 2010.06.08.
- DS/EN 1992-1-1. *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*. Dansk Standard, 2008. 3. edition.
- DS/EN 1993-1-1. *Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings*. Dansk Standard, 2007. 2. edition.
- DS/EN 1995-1-1. *Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*. Dansk Standard, 2007. 2. edition.
- A. Edgar and D. Smith. *Building Information Modeling (BIM)*, 2008. URL <http://www.wbdg.org/bim/bim.php>. 2010.06.08.
- EN 1992-1-1:2004 AC:2008. *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*. 2004.
- EN 338:2003. *Structural timber - Strength classes*. Dansk Standard, 2003.
- K. Espedokken. *IDM Makes IFC Work*, 2006. URL <http://idm.buildingsmart.no/confluence/display/IDM/IDM+Makes+IFC+Work>. 2010.06.08.
- T. Hejnfelt and R. Øksengaard. *The use of 3D and BIM technology for structural analysis and design*. Master’s thesis, DTU - Technical University of Denmark, June 2007.
- IfcWiki. *IFC - Industry Foundation Classes*, 2010a. URL [http://www.ifcwiki.org/index.php/Main\\_Page](http://www.ifcwiki.org/index.php/Main_Page). 2010.06.08.
- IfcWiki. *IFC-Developers*, 2010b. URL <http://www.ifcwiki.org/index.php/IFC-Developers>. 2010.06.08.
- R. Jardim-Goncalves and A. Grilo. Building information modeling and interoperability. *Automation in Construction*, 19(4):387 – 387, 2010.
- J. Karlshøj, H. Bell, O. J. Karud, A. Kiviniemi, and V. Tarandi. *Review of the Development and Implementation of IFC compatible BIM*. Erabuild, 2008.
- P. H. Kirkegaard and J. D. Sørensen. *A Probabilistic Approach for Robustness Evaluation of Timber Structures*. Aalborg University. Department of Civil Engineering, 2008.



- T. Liebich. *IFC Overview - Status of Standardisation, Implementation, and Use of model-based work together with IFC*, 2005. URL [http://www.iaichina.org/NewsEvents/Madrid\\_IndustryDay05/IFC%20overview%20presentation%20actual.pdf](http://www.iaichina.org/NewsEvents/Madrid_IndustryDay05/IFC%20overview%20presentation%20actual.pdf). 2010.06.08.
- T. Liebich. *IFC 2x Edition 3 Model Implementation Guide*. buildingSMART International Model Support Group, 2009.
- H. C. J. Linderoth. Understanding adoption and use of BIM as the creation of actor networks. *Automation in Construction*, 19(1):66 – 72, 2010.
- NIST. *CIS/2 and IFC - Product Data Standards for Structural Steel*, 2010. URL <http://cic.nist.gov/vrml/cis2.html>. 2010.06.08.
- P. Osterrieder and S. Richter. *IAI Project ST-5 – Structural Timber Model – Part III: Implementation Guide*. IAI, 2005.
- T. Pilgaard and G. Jonathan. *Integreret brug af BIM- og EDB værktøjer i projekteringsfasen*. Master's thesis, DTU - Technical University of Denmark, February 2010.
- Rambøll Danmark A/S. *Musikkens Hus*. URL <http://www.ramboll.dk/projects/viewproject.aspx?projectid=03DEC732-376F-4CEB-93C6-481BA499E04E>. 2010.06.08.
- R. Rasmussen and V. H. Rasmussen. *NordSoft ApS*, 2010. URL <http://www.nordsoft.net>. 2010.06.08.
- Revit Metric Tutorials. *Revit Structure 2010 - Metric Tutorials*, 2009.
- C. Robinson. Structural BIM: discussion, case studies and latest developments. *The Structural Design of Tall and Special Buildings*, 16(4):519 – 533, 2007.
- Solibri. *Solibri Model Checker*, 2010. URL <http://www.solibri.com/solibri-model-checker.html>. 2010.06.08.
- Structural Integrators. *ReadMe - SI Xchange for Revit v1.0.5.2010*, 2009.
- Structural Integrators. *SI Xchange for Revit Structure*, 2010. URL [http://structuralintegrators.com/products/si\\_xchange.php](http://structuralintegrators.com/products/si_xchange.php). 2010.06.08.
- T. Liebich. *Highlights of IFC2x4 (unveiling IFC2x4 presentation)*, 2010. URL <http://www.iai-tech.org/downloads/accompanying-documents/presentations/Unveiling%20IFC2x4.pdf>. 2010.06.08.
- Tekla. *Tekla Structures 14.0*, 2010. URL <http://www.tekla.com/international/products/tekla-structures>. 2010.06.08.
- T. S. Weir, J. D. Richardson, and D. J. Harrington. *Mastering Revit Structure 2010*. Sybex, 2009. ISBN 978-0-470-52141-0.



# Appendices



## Contents of the enclosed CD-ROM

The enclosed CD-ROM contains the following folders:

### **3-SimpleStructureSteel**

This folder contains the following files:

**SteelBeam-RVT-basis.rvt**

**SteelBeam-RVT-IFC.ifc**

**SteelBeam-RVT-RSA.rtd**

**SteelBeam-RVT-SPro.std**

### **3-SimpleStructureTimber**

This folder contains the following files:

**TimberColumn-RVT-basis.rvt**

**TimberColumn-RVT-IFC.ifc**

**TimberColumn-RVT-RSA.rtd**

**TimberColumn-RVT-SPro.std**

### **3-SimpleStructureConcrete**

This folder contains the following files:

**ReinforcedConcreteBeam-RVT-basis.rvt**

**ReinforcedConcreteBeam-RVT-IFC.ifc**

**ReinforcedConcreteBeam-RVT-RSA.rtd**

**ReinforcedConcreteBeam-RVT-SPro.std**

### **3-SimpleStructureConcreteAlternatives**

This folder contains the following files:

**ConcreteBeam-RVT-basis-for-RDesign.rvt**

**ConcreteBeam-SPro.std**

**ConcreteBeam-RDesign.rtd**

**ConcreteBeam-Intgr-w-RSA.rtd**

### **4-TimberFrameStructure**

This folder contains the following files:

**TimberFrame-Piecewise-RVT-basis.rvt**

**TimberFrame-Piecewise-RVT-RSA.rtd**

**TimberFrame-Piecewise-RVT-SPro.std**

**TimberFrame-Tapered-RVT-basis.rvt**

### **5-ImportFilesRevit**

This folder contains the following files:

**HoM-CIS2-analytical.stp**

**HoM-CIS2-drawing.stp**

**HoM-DWG.dwg**

**HoM-IFC.ifc**

### **5-Three-dimensionalSteelStructure**

This folder contains the following files:

**HoM-RVT-basis.rvt**

**HoM-RVT-RSA.rtd**

**HoM-RVT-SPro.std**

### **Thesis**

This folder contains the following pdf file:

**Structural-modelling-and-analysis-using-BIM-tools.pdf**

## E-mail correspondence with Elizabeth Shulok from Structural Integrators

---

In this Appendix the main essence of the correspondence with Elizabeth Shulok from Structural Integrators regarding *SI Xchange for Revit and STAAD* is presented.

---

### B.1 Questions and answers

- Q: It is not possible to update our model in Revit from StaadPro. It seems like it is the wrong software we have installed?
- A: There might be a misunderstanding how SI Xchange works. Its current capabilities allow you to export a model from Revit to StaadPro and then update Revit with some of the changes made in StaadPro. With the current version, you cannot import a new model from StaadPro to Revit. That will be in a future release.
- Q: We have tried setting the default up-coordinate in StaadPro to both Y and Z. In both cases the beam is oriented as shown earlier (with Y up and Z lengthwise) and the roller BC is defined as ffxfff.
- A: Regarding the coordinate system, SI Xchange assumes you are using the default Y up system since there wasn't an easy way to check this during export. So the coordinates are translated accordingly. Please try the export with the Y up coordinate system selected and let me know if it is still incorrect. The BC change are not currently sent back to Revit. Only the size changes and column rotations are being updated in Revit. The next release will update significantly more data. Thank you for the feedback on the BCs. I will need to investigate that. You shouldn't need to adjust them in StaadPro.
- Q: It is not possible to change the material in StaadPro and then update back to Revit. Will this be available in a future release?
- A: In the current version, only sizes of the same material will be updated in Revit. That will not be the case in the next release that we are working on now. However, the new version will only work with Revit Structure 2011.
- Q: We started using SI Xchange for a timber structure and found that the shape maps only support steel and concrete sections. Thus the sections were not transferred to StaadPro, and when added in StaadPro, not transferred back to Revit either. Is it possible to add shape maps for timber so this will be possible?

## **B. E-mail correspondence with Elizabeth Shulok from Structural Integrators**

---

A: SI Xchange currently only supports steel and concrete materials. We have not had any requests to support wood structures so it has not been a priority for us.



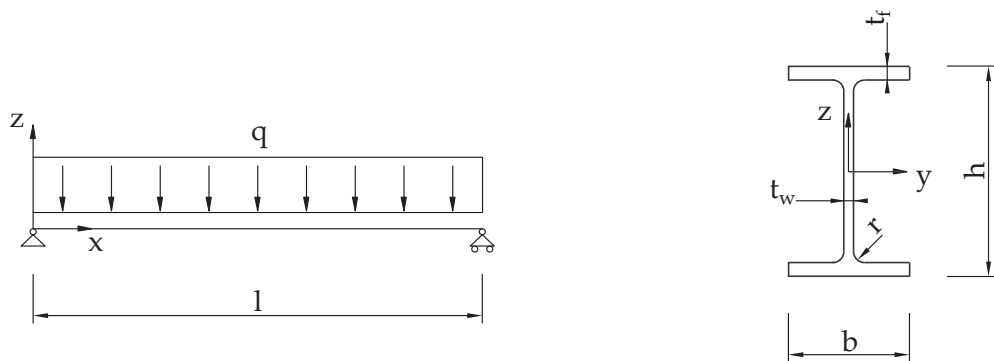
## Simply supported steel beam

The design parameters and procedure described in this appendix form the basis of the tests performed in Section 3.3.

### C.1 Design parameters

In this appendix the relevant parameters in connection with the design criteria of the 6 m simply supported steel beam are presented. The beam is an IPE200-profile of steel type S235.

The statical system of the steel beam and the cross section are shown in Figure C.1 whereas the parameters related to the cross section are shown in Table C.1. The parameters at the top of the table must be defined whereas the parameters at the bottom can be calculated from the parameters at the top.



**Figure C.1** Left: Simply supported beam. Right: Cross section of an IPE profile.

## C. Simply supported steel beam

| Section properties |            |                   |                 |
|--------------------|------------|-------------------|-----------------|
| Section class      |            | I                 |                 |
| Height             | $h$        | 200               | mm              |
| Width              | $b$        | 100               | mm              |
| Web thickness      | $t_w$      | 5.6               | mm              |
| Flange thickness   | $t_f$      | 8.5               | mm              |
| Radius             | $r$        | 12                | mm              |
| Area               | $A$        | $2.85 \cdot 10^3$ | mm <sup>2</sup> |
| Shear area         | $A_z$      | $1.40 \cdot 10^3$ | mm <sup>2</sup> |
| Moment of inertia  | $I_y$      | $19.4 \cdot 10^6$ | mm <sup>4</sup> |
| Moment of inertia  | $I_z$      | $1.42 \cdot 10^6$ | mm <sup>4</sup> |
| Torsion constant   | $I_t$      | $70.2 \cdot 10^3$ | mm <sup>4</sup> |
| Warping constant   | $I_w$      | $12 \cdot 10^9$   | mm <sup>6</sup> |
| Elastic modulus    | $W_{el,y}$ | $194 \cdot 10^3$  | mm <sup>3</sup> |
| Plastic modulus    | $W_{pl,y}$ | $220 \cdot 10^3$  | mm <sup>3</sup> |
| Radius of gyration | $i$        | 82.57             | mm              |

Table C.1 Parameters in relation to the cross section.

The relevant geometric parameters are shown in Table C.2.

| Geometry         |           |      |    |
|------------------|-----------|------|----|
| Length           | $l$       | 6000 | mm |
| Effective length | $l_{eff}$ | 6000 | mm |

Table C.2 Geometry parameters.

The parameters that define the material steel S235 are presented in Table C.3.

| Material properties   |        |                   |                   |
|-----------------------|--------|-------------------|-------------------|
| Yield stress          | $f_y$  | 235               | MPa               |
| Modulus of elasticity | $E$    | $205 \cdot 10^3$  | MPa               |
| Shear modulus         | $G$    | $78.8 \cdot 10^3$ | MPa               |
| Density               | $\rho$ | 76.8195           | kN/m <sup>3</sup> |

Table C.3 Material parameters.

As described in Section 3.3 the line load is set to 5 kN/m which also can be seen in Table C.4.

| Load      |         |   |      |
|-----------|---------|---|------|
| Magnitude | $q$     | 5 | kN/m |
| Position  | Element | 1 | -    |

Table C.4 Load parameters.

For a simply supported beam the boundary conditions are defined in Table C.5. In the table

$f$  marks a free degree of freedom whereas  $x$  marks a fixed degree of freedom. The three first positions are related to the translations in the three directions ( $x, y$  and  $z$ ) and the three last positions are related to the rotations about the three directions.

| Boundary conditions |    |           |
|---------------------|----|-----------|
| <b>Pinned</b>       | S1 | $xxxfff$  |
| <b>Roller</b>       | S2 | $fxxffff$ |

**Table C.5** Boundary conditions.

To be able to assess the design criteria the applied applications must be able to find the parameters given in Table C.6.

| Design data  |               |       |     |
|--|---------------|-------|-----|
| <b>Moment capacity</b>                                 | $M_{c,R}$     | 47.0  | kNm |
| <b>Shear capacity</b>                                  | $V_{c,R}$     | 172.9 | kN  |
| <b>Reduction factor for lateral torsional buckling</b> | $\chi_{LT}$   | 0.45  | -   |
| <b>Imperfection factor</b>                             | $\alpha_{LT}$ | 0.21  | -   |
| <b>Buckling curve</b>                                  |               | a     | -   |
| <b>Lateral torsional buckling moment capacity</b>      | $M_{b,R}$     | 18.6  | kNm |

**Table C.6** Parameters in relation to design.

The results of the hand calculations of the IPE 200 profile is shown in Table C.7

| Results               |                 |      |    |
|-----------------------|-----------------|------|----|
| <b>Deflection</b>     | $u_{\max}$      | 22   | mm |
| <b>Section forces</b> | $M_{\max}$      | 23.5 | kN |
|                       | $V_{\max}$      | 15.7 | kN |
| <b>EC3 6.2.5</b>      | $M_E / M_{c,R}$ | 0.5  | -  |
| <b>EC3 6.2.6 (Z)</b>  | $V_E / V_{c,R}$ | 0.09 | -  |
| <b>EC3 6.3.2 LTB</b>  | $V_E / V_{c,R}$ | 1.26 | -  |

**Table C.7** Results of hand calculations for the steel beam with cross section IPE 200.

To be characterized as useful the S-BIM tools must be able to handle the parameters described above. The parameters are all used in relation to the evaluation of tests performed for the steel beam.

### C.2 Procedure of tests

The procedures leading to the results in Table 3.1 are described in the following. The employed models can be found at the enclosed CD-ROM in the folder *3-SimpleStructureSteel*.

#### Revit add-on tool (RVT add-on)

The results in the add-on tool are obtained very easy.

- Revit Extensions, Simulation - Static Analysis of Frames:
  1. Calculations → Results (Only section forces and deflection. I.e. no code check is available.)

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

To obtain the correct results in Robot some choices and a correction are necessary.

- Revit Extensions, Integration with Robot Structural Analysis (Send model):
  1. Choice about model correction in Robot
  2. Choice about bar end releases
  3. Choice about materials
- Robot:
  4. Verification → No errors and no warnings are found
  5. Manually define element type as beam
  6. Calculation → Two irrelevant warnings → Results (Section forces and deflection.)
  7. Code check → Results (Section forces, deflection and code check.)

To update the model in Revit from the analysis in Robot, some choices are needed.

- Robot:
  8. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  9. New code check
- Revit Extensions, Integration with Robot Structural Analysis (Update model):
  10. Choice about scope
  11. Nothing happens to the model in Revit except for when changing the section properties

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

To obtain the correct results in StaadPro some choices and a correction are necessary.

- SI Xchange (Export):
  1. Choice about shape maps
  2. Choice about units

- StaadPro:
  3. Manually add self weight
  4. Choose type of analysis (Analysis/Print: All, Design - Steel: EC3)  
→ Results (Section forces, deflection and code check.)

Note: Coordinate system different from Revit and Robot.

To update the model in Revit from the analysis in StaadPro, some choices are needed.

- StaadPro:
  5. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  6. New code check
- SI Xchange (Import):
  7. Nothing happens to the model in Revit except for when changing the section properties

**Indirect link from Revit to Robot ( $RVT \xrightarrow{IFC} RSA$ )**

It has not been possible to obtain results from Robot by use of the IFC exchange file format, since only some of the geometry was imported.

- Revit:
  1. Export to IFC file
- Robot:
  2. Open IFC file (Note: Only geometry appears.)
  3. Verification
    - Error: Bar without properties
    - Warnings: No supports, no load cases, the element is not assigned to any story



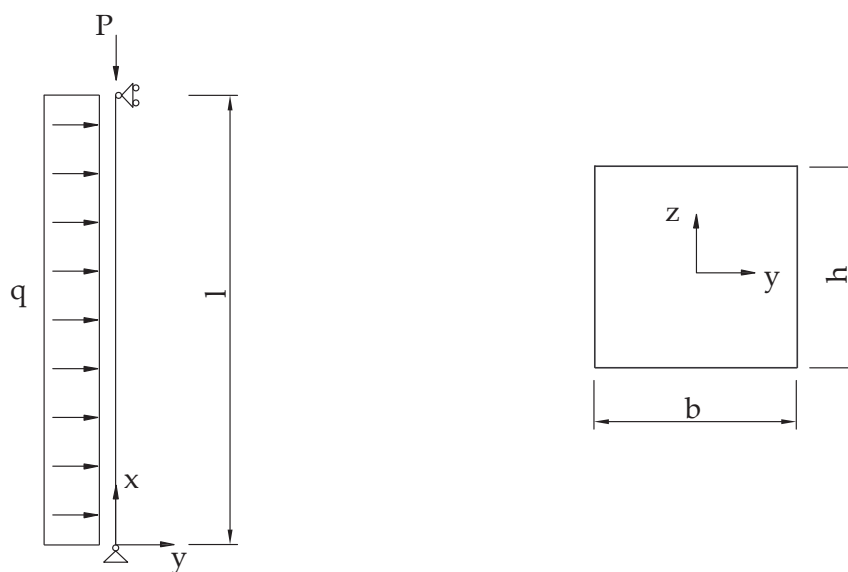
## Simply supported timber column

The design parameters and procedure described in this appendix form the basis of the tests performed in Section 3.4.

### D.1 Design parameters

The parameters needed to evaluate the design criterion are presented in the following tables.

The statical system of the timber column and the cross section are shown in Figure D.1 whereas the parameters related to the cross section are shown in Table D.1.



**Figure D.1** Left: Simply supported column. Right: Cross section.

| Section properties |            |                    |               |
|--------------------|------------|--------------------|---------------|
| Height             | $h$        | 150                | mm            |
| Width              | $b$        | 150                | mm            |
| Area               | $A$        | $22.5 \cdot 10^3$  | $\text{mm}^2$ |
| Moment of inertia  | $I_y$      | $42.2 \cdot 10^6$  | $\text{mm}^4$ |
| Elastic modulus    | $W_{el,y}$ | $562.5 \cdot 10^3$ | $\text{mm}^3$ |

**Table D.1** Parameters in relation to the cross section.

## D. Simply supported timber column

The relevant geometric parameters are shown in Table D.2.

| Geometry |     |      |    |
|----------|-----|------|----|
| Length   | $l$ | 3000 | mm |

Table D.2 Geometry parameters.

The parameters that define the anisotropic material timber C24 are presented in Table D.3.

| Material properties                                   |             |       |                   |
|---|-------------|-------|-------------------|
| Characteristic bending strength                       | $f_{m,k}$   | 24,0  | MPa               |
| Characteristic compressive strength parallel to grain | $f_{c,0,k}$ | 21    | MPa               |
| Characteristic modulus of elasticity                  | $E_k$       | 7400  | MPa               |
| Density   | $\rho$      | 3.432 | kN/m <sup>3</sup> |

Table D.3 Material parameters.

As described in Section 3.4 the point load is 20 kN and the line load is 5 kN/m as shown in Table D.4.

| Loads                  |               |    |      |
|------------------------|---------------|----|------|
| Point load - magnitude | $P$           | 20 | kN   |
| Point load - position  | Element       | 1  | -    |
| Point load - duration  | Permanent     | -  | -    |
| Line load - magnitude  | $q$           | 5  | kN/m |
| Line load - position   | Element       | 1  | -    |
| Line load - duration   | Instantaneous | -  | -    |

Table D.4 Load parameters.

For the simply supported column the boundary conditions are defined in Table D.5.

| Boundary conditions |    |        |
|---------------------|----|--------|
| Pinned              | S1 | xxxfff |
| Roller              | S2 | fxxfff |

Table D.5 Boundary conditions.

To be able to assess the design criterion the applied applications must be able to find the parameters given in Table D.6.



| Design data                       |           |       |     |
|-----------------------------------|-----------|-------|-----|
| Allowable bending stress (I-load) | $f_{m,d}$ | 20.31 | MPa |
| Allowable normal stress (I-load)  | $f_{c,d}$ | 17.77 | MPa |
| Allowable normal stress (P-load)  | $f_{c,d}$ | 9.69  | MPa |
| Modification factor (I-load)      | $k_{mod}$ | 1.1   | -   |
| Modification factor (P-load)      | $k_{mod}$ | 0.6   | -   |
| Instability factor                | $k_c$     | 0.56  | -   |
| Service class                     |           | 1     | -   |

**Table D.6** Parameters in relation to design.

The results of the hand calculations of the timber profile is shown in Table D.7

| Results        |   |      |     |
|----------------|---|------|-----|
| Section forces | $M_{\max}$  | 5.3  | kNm |
|                | $N_{\max}$  | 20   | kN  |
| EC5 6.3.2      | $\frac{\sigma_c}{k_c \cdot f_c} + \frac{\sigma_m}{f_m}$ | 0.58 | -   |

**Table D.7** Results of hand calculations for the timber column with cross section  $150 \times 150$  mm.

### D.2 Procedure of tests

The procedure leading to the results in Table 3.2 are in principle the same as described in Appendix C.2. To keep a sense of perspective the exact procedure for the timber column are described in the following. The employed models can be found at the enclosed CD-ROM in the folder *3-SimpleStructureTimber*.

#### Revit add-on tool (RVT add-on)

No correct results could be obtained by use of the Revit add-on tool

- Revit Extensions, Simulation - Static Analysis of Frames:
  1. Calculations → Results (Only section forces, which are wrong. I.e. no code check is available and the results are useless.)

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

To obtain the correct results in Robot some choices are necessary.

- Revit Extensions, Integration with Robot Structural Analysis (Send model):
  1. Choice about model correction in Robot
  2. Choice about bar end releases
  3. Choice about materials
- Robot:
  4. Verification → No errors and no warnings are found
  5. Manually define element type as Timber column
  6. Define load duration
  7. Calculation → Two irrelevant warnings → Results (Section forces and deflection.)
  8. Code check → Results (Section forces, deflection and code check.)

To update the model in Revit from the analysis in Robot, some choices are needed.

- Robot:
  9. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  10. New code check
- Revit Extensions, Integration with Robot Structural Analysis (Update model):
  11. Choice about scope
  12. Nothing happens to the model in Revit except for when changing the section properties

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

To obtain the correct results in StaadPro some choices and corrections are necessary.

- SI Xchange (Export):

1. Choice about shape maps
  2. Choice about units
- StaadPro:
    3. Redefine BC's
    4. Redefine cross section
    5. Manually add self weight
    6. Choose type of analysis (Analysis/Print: All, Design - Timber: EC5 (define load duration, member type and section class))
      - Results (Section forces, deflection and code check.)

Note: Coordinate system different from Robot.

To update the model in Revit from the analysis in StaadPro, some choices are needed.

- StaadPro:
  7. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  8. New code check
- SI Xchange (Import):
  9. Nothing happens to the model in Revit

#### **Indirect link from Revit to Robot (RVT $\xrightarrow{\text{IFC}}$ RSA)**

It has not been possible to obtain results from Robot by use of the IFC exchange file format, since only the length and cross section was imported.

- Revit:
  1. Export to IFC file
- Robot:
  2. Open IFC file (Note: Only geometry and some section properties appears.)
  3. Verification
    - Warnings: No supports, no load cases, the element is not assigned to any story



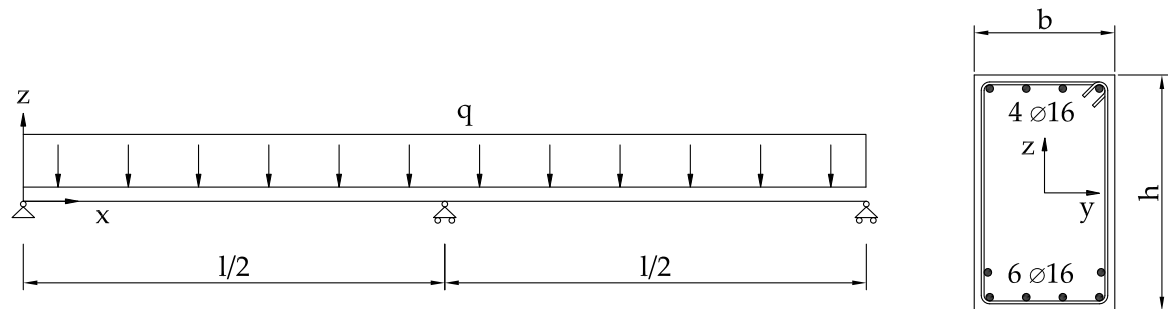
## Continuous concrete beam

The design parameters and procedure described in this appendix form the basis of the tests performed in Section 3.5.

### E.1 Design parameters

The parameters needed to evaluate the design criteria are presented in the following tables.

The statical system of the concrete beam and the cross section are shown in Figure E.1. The total length of the beam is 12.6 m and it is supported by one pinned and two roller supports. The parameters related to the cross section are shown in Table E.1.



**Figure E.1** Left: Continuous beam. Right: Cross section.

| Section properties                       |                     |                   |                 |
|--|---------------------|-------------------|-----------------|
| Height                                   | $h$                 | 500               | mm              |
| Width                                    | $b$                 | 300               | mm              |
| Moment of inertia                        | $I_y$               | $3125 \cdot 10^6$ | mm <sup>4</sup> |
| Effective height, between supports       | $d$                 | 453.3             | mm              |
| Effective height, at centre support      | $d$                 | 471               | mm              |
| Internal moment arm, between supports    | $z$                 | 399.9             | mm              |
| Internal moment arm, at centre support   | $z$                 | 435.4             | mm              |
| Diameter of reinforcement                | $\varnothing$       | 16                | mm              |
| Reinforcement bars, top                  |                     | 4                 | -               |
| Reinforcement bars, bottom               |                     | 6                 | -               |
| Diameter of stirrups                     | $\varnothing$       | 6                 | mm              |
| Spacing of stirrups, $x$ :0–220 mm       | $s$                 | 110               | mm              |
| Spacing of stirrups, $x$ :220–12380 mm   | $s$                 | 330               | mm              |
| Spacing of stirrups, $x$ :12380–12600 mm | $s$                 | 110               | mm              |
| Position of reinforcement                | $c_{s1}/c_{s2}/c_s$ | 29/53/47          | mm              |

Table E.1 Parameters in relation to the cross section.

The relevant geometric parameters are shown in Table E.2.

| Geometry         |           |       |    |
|------------------|-----------|-------|----|
| Total length     | $l$       | 12600 | mm |
| Effective length | $l_{eff}$ | 6300  | mm |

Table E.2 Geometry parameters.

The parameters that define the concrete C25/30 and reinforcing steel S550 are presented in Table E.3.

| Material properties                    |                     |                |                   |
|--|---------------------|----------------|-------------------|
| Yield strength of reinforcement        | $f_{yk}$            | 550            | MPa               |
| Modulus of elasticity of reinforcement | $E_s$               | $2 \cdot 10^6$ | MPa               |
| Compression strength of concrete       | $f_{ck}$            | 25             | MPa               |
| Axial tensile strength of concrete     | $f_{ctm}$           | 2.6            | MPa               |
| Modulus of elasticity of concrete      | $E$                 | 32000          | MPa               |
| Density                                | $\rho$              | 23.5           | kN/m <sup>3</sup> |
| Ultimate compressive strain            | $\varepsilon_{cu3}$ | 0.0035         | -                 |

Table E.3 Material parameters.

As described in Section 3.5 the line load is set to 50 kN/m which also can be seen in Table E.4.

| Load             |         |    |      |
|------------------|---------|----|------|
| <b>Magnitude</b> | $q$     | 50 | kN/m |
| <b>Position</b>  | Element | 1  | -    |

Table E.4 Load parameters.

For a continuous beam the boundary conditions are defined in Table E.5.

| Boundary conditions |    |     |     |
|---------------------|----|-----|-----|
| <b>Pinned</b>       | S1 | xxx | fff |
| <b>Roller</b>       | S2 | fxx | fff |

Table E.5 Boundary conditions.

To be able to assess the design criteria the applied applications must be able to find the parameters given in Table E.6.

| Design data   |                |       |     |
|---|----------------|-------|-----|
| <b>Control class</b>                                  |                | 2     | -   |
| <b>Environmental class</b>                            |                | 1     | -   |
| <b>Allowance</b>                                      |                | 5     | mm  |
| <b>Maximum aggregate size</b>                         | $d_g$          | 32    | mm  |
| <b>Moment capacity, between supports</b>              | $M_R$          | 221.1 | kNm |
| <b>Moment capacity, at centre support</b>             | $M_R$          | 160.5 | kNm |
| <b>Factor <math>\lambda</math></b>                    | $\lambda$      | 0.8   | -   |
| <b>Reinforcement degree</b>                           | $\omega_{bal}$ | 0.483 | -   |
| <b>Reinforcement degree</b>                           | $\omega_{min}$ | 0.033 | -   |
| <b>Actual reinforcement degree, between supports</b>  | $\omega$       | 0.24  | -   |
| <b>Actual reinforcement degree, at centre support</b> | $\omega$       | 0.15  | -   |
| <b>Factor <math>\mu</math></b>                        | $\mu$          | 0.2   | -   |

Table E.6 Parameters in relation to design.

The results of the hand calculations of the continuous reinforced concrete beam is shown in Table E.7

| Results                                      |                   |                            |     |
|--|-------------------|----------------------------|-----|
| <b>Deflection</b>                            | $u_{max}$         | 4.6                        | mm  |
| <b>Section forces</b>                        | $M_{max}$         | 200.6                      | kNm |
|  | $V_{max}$         | 189.3                      | kN  |
| $\omega_{min} \leq \omega \leq \omega_{bal}$ | Between supports  | $0.03 \leq 0.24 \leq 0.48$ | -   |
|  | At centre support | $0.03 \leq 0.15 \leq 0.48$ | -   |
| $M_R \geq M$                                 | Between supports  | $221.1 \geq 200.6$         | kNm |
|  | At centre support | $160.5 \geq 130$           | kNm |
| $\sigma_c \leq \nu_v f_{cd}$                 | At centre support | $3.6 \geq 9.9$             | MPa |

Table E.7 Results of hand calculations for the reinforced concrete beam with cross section 300 x 500 mm.

### E.2 Procedure of tests

The procedure leading to the results in Table 3.3 are in principle the same as described in Appendix C.2 and D.2. To keep a sense of perspective the exact procedure for the continuous concrete beam are described in the following. The employed models can be found at the enclosed CD-ROM in the folder *3-SimpleStructureConcrete*.

#### Revit add-on tool (RVT add-on)

The results in the add-on tool are obtained very easy.

- Revit Extensions, Simulation - Static Analysis of Frames:
  1. Calculations → Results (Only section forces and deflection.)

#### Direct link from Revit to Robot (RVT→RSA)

To obtain the correct results in Robot some choices are necessary.

- Revit Extensions, Integration with Robot Structural Analysis (Send model):
  1. Choice about model correction in Robot
  2. Choice about bar end releases
  3. Choice about materials
- Robot:
  4. Verification → No errors and no warnings are found
  5. Calculation → Two irrelevant warnings → Results (Only section forces and deflection.)

The performed analysis gives no results related to the design criteria. How reinforcement can be modelled in Robot can be seen in Section 3.5.3 regarding alternative procedures.

#### Direct link from Revit to StaadPro (RVT→SPro)

To obtain the correct results in StaadPro some choices and a correction are necessary.

- SI Xchange (Export):
  1. Choice about shape maps
  2. Choice about units
- StaadPro:
  3. Redefine boundary conditions (Wrong because the coordinate system is different from Revit.)
  4. Manually add self weight
  5. Choose type of analysis (Analysis/Print: All) → Results (Only section forces and deflection.)

The performed analysis gives no results related to the design criteria. How reinforcement can be handled in StaadPro can be seen in Section 3.5.3 regarding alternative procedures.



**Indirect link from Revit to Robot (RVT  $\xrightarrow{\text{IFC}}$  RSA)**

It has not been possible to obtain results from Robot by use of the IFC exchange file format, since only some of the geometry and section properties was imported.

- Revit:
  1. Export to IFC file
- Robot:
  2. Open IFC file (Note: Only geometry and some section properties appears.)
  3. Verification
    - Warnings: No supports, no load cases, the element is not assigned to any story

**E.3 Procedure of alternatives**

In this appendix alternative possibilities for data exchange of the reinforced concrete beam are described. The employed models can be found at the enclosed CD-ROM in the folder *3-SimpleStructureConcreteAlternatives*.

**Common procedure for all three alternatives**

Due to the procedure in *Robot*, *RC Beam Design* the supports must be changed.

- Revit:
  1. Add columns (500 × 300 mm) instead of boundary conditions
  2. Add boundary conditions to columns (Fixed)

**Alternative 1: Revit Extensions, Reinforcement Design**

This extension makes use of the RC Beam Design module of Robot where the layout of the necessary amount of reinforcement is found. Furthermore it is possible to update the Revit model with the reinforcement found in Robot.

- Revit Extensions, Reinforcement Design:
  1. Choice about steel type (550 MPa)
- Robot, RC Beam Design
  2. Define reinforcement pattern
  3. Set calculation options
  4. Change load factor of self weight to 1
  5. Add line load of 50 kN/m<sup>2</sup>
  6. Calculations → Results (Top: 8Ø16, Bottom: 10Ø16)
- Revit Extensions, Reinforcement Design:
  7. Import the reinforcement from Robot

### Alternative 2: Revit Extensions, Integration with Robot Structural Analysis

In this alternative use have been made of the same integration with Robot as in Appendix E.2, but here it is used to utilize the *RC Members - required reinf.* module in Robot. Updating the calculated reinforcement back to Revit is not possible.

- Revit Extensions, Integration with Robot Structural Analysis (Send model):
  1. Choice about model correction in Robot
  2. Choice about bar end releases
  3. Choice about materials
- Robot:
  4. Manually define element type as RC beam
  5. Calculations → two irrelevant warnings
  6. Define reinforcement calculations parameters
  7. Define calculation points
  8. Calculations → Results (Top: 7Ø16, Bottom: 3Ø16)

### Alternative 3: SI Xchange → StaadPro, Design - Concrete: EC2

The following procedure enables StaadPro to calculate the necessary amount of reinforcement in the concrete beam. Updating the calculated reinforcement back to Revit is not possible.

- SI Xchange (Export):
  1. Choice about shape maps
- StaadPro:
  2. Manually add self weight
  3. Add analysis (All)
  4. Define parameters of Design concrete (EC2)
  5. Calculations → Results (Top: 8Ø16, Bottom: 4Ø16)

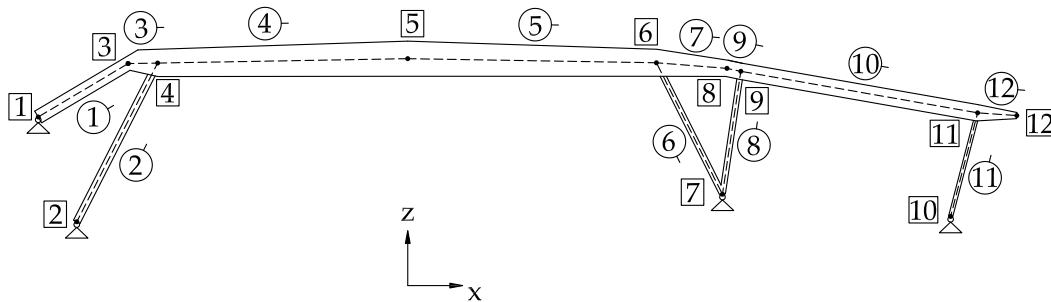
## Timber frame structure

The design parameters and procedure described in this appendix form the basis of the tests performed in Chapter 4.

### F.1 Design parameters

The parameters needed to evaluate the design criteria in Section 4.3 are presented in the following tables.

The modelled timber frame structure is shown in Figure F.1 whereas the parameters related to the cross section are shown in Table F.1 and F.2.



**Figure F.1** The element and node numbers for the timber frame structure.

| Section properties |            |      |     |      |      |     |       |       |     |                           |
|--------------------|------------|------|-----|------|------|-----|-------|-------|-----|---------------------------|
| Element            |            | 1    | 3   | 4    | 5    | 7   | 9     | 10    | 12  |                           |
| Start height       | $h_1$      | 480  | 480 | 960  | 1250 | 960 | 580   | 580   | 580 | mm                        |
| End height         | $h_2$      | 480  | 960 | 1250 | 960  | 580 | 580   | 580   | 220 | mm                        |
| Width              | $b$        | 200  | 200 | 200  | 200  | 200 | 200   | 200   | 200 | mm                        |
| Area               | $A$        | 96.0 | var | var  | var  | var | 116.0 | 116.0 | var | $\cdot 10^3 \text{ mm}^2$ |
| Moment of inertia  | $I_y$      | 1843 | var | var  | var  | var | 3252  | 3252  | var | $\cdot 10^6 \text{ mm}^4$ |
| Elastic modulus    | $W_{el,y}$ | 7680 | var | var  | var  | var | 11210 | 11210 | var | $\cdot 10^3 \text{ mm}^3$ |

**Table F.1** Parameters in relation to the cross section for the beams.

| Section properties |            |       |       |       |       |                           |
|--------------------|------------|-------|-------|-------|-------|---------------------------|
| Element            |            | 2     | 6     | 8     | 11    |                           |
| Start height       | $h_1$      | 260   | 200   | 200   | 150   | mm                        |
| End height         | $h_2$      | 260   | 200   | 200   | 150   | mm                        |
| Width              | $b$        | 260   | 200   | 200   | 200   | mm                        |
| Area               | $A$        | 67.6  | 40.0  | 40.0  | 30.0  | $\cdot 10^3 \text{ mm}^2$ |
| Moment of inertia  | $I_y$      | 380.8 | 133.3 | 133.3 | 56.25 | $\cdot 10^6 \text{ mm}^4$ |
| Elastic modulus    | $W_{el,y}$ | 2929  | 1333  | 1333  | 750   | $\cdot 10^3 \text{ mm}^3$ |

Table F.2 Parameters in relation to the cross section for the columns.

The relevant geometric parameters for the beams and columns are shown in Table F.3 and F.4, respectively.

| Geometry |     |      |      |      |      |      |     |      |      |
|----------|-----|------|------|------|------|------|-----|------|------|
| Element  |     | 1    | 3    | 4    | 5    | 7    | 9   | 10   | 12   |
| Length   | $l$ | 3722 | 1050 | 8901 | 8851 | 2518 | 504 | 8563 | 1398 |
|          |     |      |      |      |      |      |     |      | mm   |

Table F.3 Geometry parameters for the beams.

| Geometry |     |      |      |      |      |    |
|----------|-----|------|------|------|------|----|
| Element  |     | 2    | 6    | 8    | 11   |    |
| Length   | $l$ | 6339 | 5237 | 4424 | 3811 | mm |

Table F.4 Geometry parameters for the columns.

The parameters that define the anisotropic material glulam timber Gl36c are presented in Table F.5.

| Material properties                                    |              |       |                   |
|--|--------------|-------|-------------------|
| Characteristic bending strength                        | $f_{m,k}$    | 36.0  | MPa               |
| Characteristic tensile strength parallel to grain      | $f_{t,0,k}$  | 22.5  | MPa               |
| Characteristic tensile strength perpendicular to grain | $f_{t,90,k}$ | 0.5   | MPa               |
| Characteristic compressive strength parallel to grain  | $f_{c,0,k}$  | 36.0  | MPa               |
| Characteristic shear strength                          | $f_{v,k}$    | 3.8   | MPa               |
| Characteristic modulus of elasticity                   | $E_k$        | 14700 | MPa               |
| Characteristic value of shear modulus                  | $G$          | 7350  | MPa               |
| Density  | $\rho$       | 4.22  | kN/m <sup>3</sup> |

Table F.5 Material parameters.

As described in Section 4.3 two line loads are acting on the timber frame structure in addition to the self weight of the frame. The loads are shown in Table F.6.

| Loads                 |            |                             |     |      |
|-----------------------|------------|-----------------------------|-----|------|
| Line load - magnitude | $p$        |                             | 7.5 | kN/m |
| Line load - position  | Elements   | 1, 3, 4, 5, 7, 9, 10 and 12 | -   |      |
| Line load - duration  | Permanent  |                             | -   |      |
| Line load - magnitude | $q$        |                             | 15  | kN/m |
| Line load - position  | Elements   | 1, 3, 4, 5, 7, 9, 10 and 12 | -   |      |
| Line load - duration  | Short term |                             | -   |      |

Table F.6 Load parameters.

For the timber frame structure, the releases and supports shown in Figure F.2 should be defined as shown in Table F.7 and F.8, respectively.

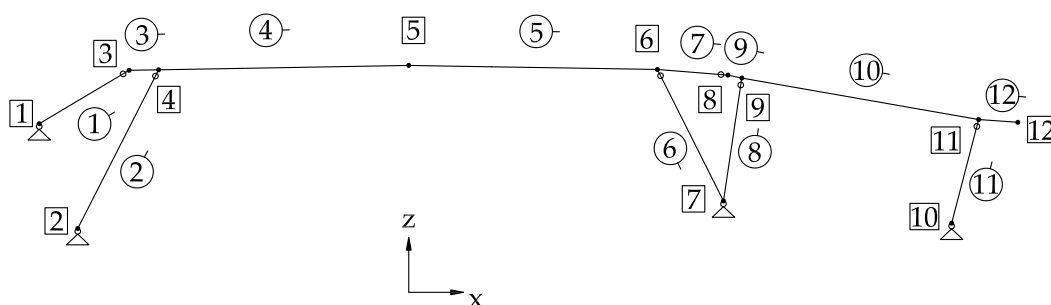


Figure F.2 The releases and supports for the timber frame structure.

| Boundary conditions |        |       |       |       |        |       |       |       |
|---------------------|--------|-------|-------|-------|--------|-------|-------|-------|
| Element             | 1      | 3     | 4     | 5     | 7      | 9     | 10    | 12    |
| Start node          | 1      | 3     | 4     | 5     | 6      | 8     | 9     | 11    |
| End node            | 3      | 4     | 5     | 6     | 8      | 9     | 11    | 12    |
| Start releases      | Fixed  | Fixed | Fixed | Fixed | Fixed  | Fixed | Fixed | Fixed |
| End releases        | Pinned | Fixed | Fixed | Fixed | Pinned | Fixed | Fixed | Fixed |
| Support             | xxxfff | -     | -     | -     | -      | -     | -     | -     |

Table F.7 Boundary conditions for the beams.

| Boundary conditions |        |        |        |        |
|---------------------|--------|--------|--------|--------|
| Element             | 2      | 6      | 8      | 11     |
| Start node          | 2      | 6      | 7      | 10     |
| End node            | 4      | 7      | 9      | 11     |
| Start releases      | Fixed  | Pinned | Fixed  | Fixed  |
| End releases        | Pinned | Fixed  | Pinned | Pinned |
| Support             | xxxfff | xxxfff | xxxfff | xxxfff |

Table F.8 Boundary conditions for the columns.

To be able to assess the design criteria the applied applications must be able to find the parameters given in Table F.9.

| Design data                         |              |       |     |
|-------------------------------------|--------------|-------|-----|
| Allowable bending stress            | $f_{m,d}$    | 24.92 | MPa |
| Allowable tensile stress            | $f_{t,0,d}$  | 15.58 | MPa |
| Allowable tensile stress            | $f_{t,90,d}$ | 0.35  | MPa |
| Allowable normal stress             | $f_{c,0,d}$  | 24.92 | MPa |
| Allowable shear stress              | $f_{v,d}$    | 2.63  | MPa |
| Modification factor                 | $k_{mod}$    | 0.9   | -   |
| Instability factor                  | $k_{c,y}$    | var   | -   |
| Factor for lateral buckling         | $k_{crit}$   | var   | -   |
| Factor                              | $k_p$        | var   | -   |
| Volume factor                       | $k_{vol}$    | 1.0   | -   |
| Factor for distribution of stresses | $k_{dis}$    | 1.4   | -   |
| Service class                       |              | 1     | -   |

Table F.9 Parameters in relation to design.

The section forces in the timber frame structure are shown in Figure F.3, F.4 and F.5 whereas the results obtained according to the design criteria in Section 4.3 are shown in Table F.10.

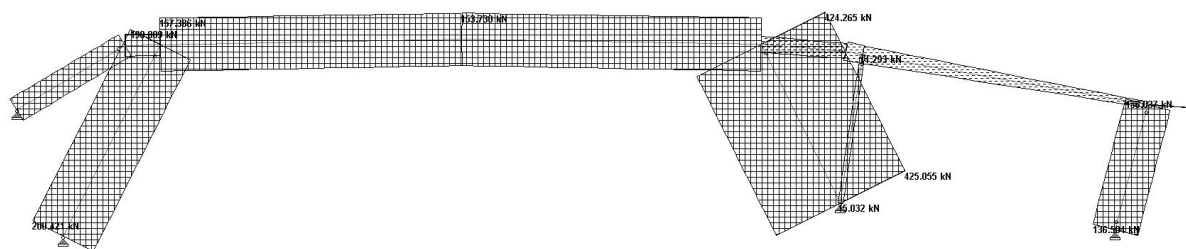


Figure F.3 Distribution of axial forces for the timber frame structure.

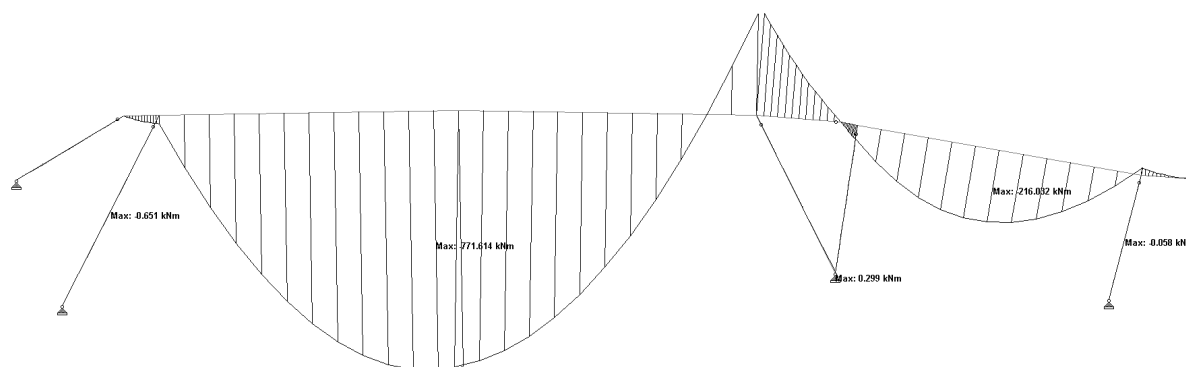


Figure F.4 Moment distribution for the timber frame structure.

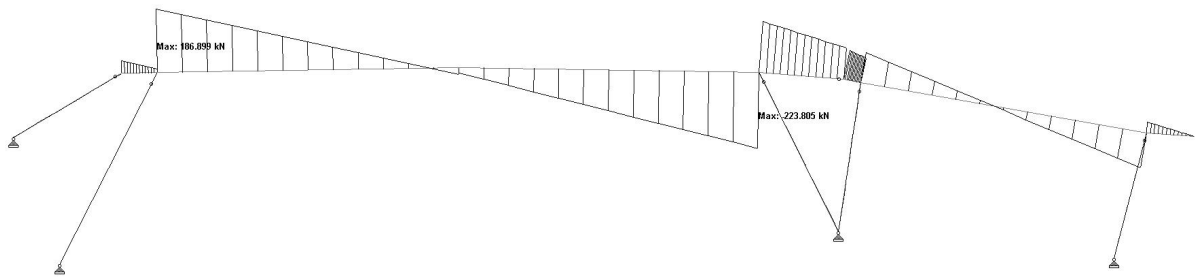


Figure F.5 Distribution of shear forces for the timber frame structure.

| Results   |   |            |      |    |
|-----------|---|------------|------|----|
| EC5 6.3.2 | $\frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,0,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}}$                           | Element 2  | 0.26 | -  |
|           |   | Element 6  | 1.04 | -  |
|           |   | Element 8  | 0.04 | -  |
|           |   | Element 11 | 0.28 | -  |
| EC5 6.3.3 | $\frac{\sigma_{c,d}}{k_{c,y} \cdot f_{c,0,d}} + \left( \frac{\sigma_{m,d}}{k_{crit} \cdot f_{m,d}} \right)^2$ | Node 5     | 0.39 | -  |
| EC5 6.2.3 | $\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}}$   | Element 10 | 0.79 | -  |
| EC5 6.1.7 | $\frac{\tau_d}{f_{v,d}}$  | Node 4     | 0.56 | -  |
|           |   | Node 6     | 0.67 | -  |
| EC5 6.4.3 | $\frac{\tau_d}{f_{v,d}} + \frac{\sigma_{t,90,d}}{k_{dis} \cdot k_{vol} \cdot f_{t,90,d}}$                     | Node 5     | 0.25 | -  |
| EC5 7.2   | $w_{fin}$   | Node 5     | 63.3 | mm |

Table F.10 Results of initial calculations for the timber frame structure.

## F.2 Updated parameters

The changed parameters for the model where the tapered beams are modelled as pieces of beams with constant rectangular cross section are presented the following.

The modelled timber frame structure are shown in Figure F.6 whereas the changed parameters related to the cross section are shown in Table F.11.

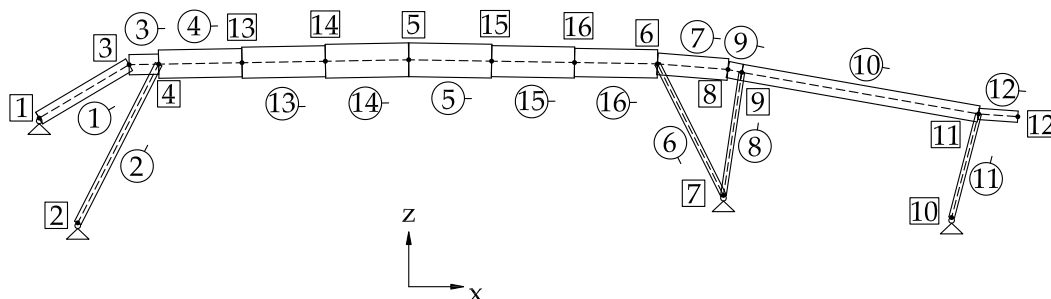


Figure F.6 The element and node numbers for the timber frame structure where the tapered beams are replaced by beams with constant section height.

## F. Timber frame structure

| Section properties |            |       |       |       |       |      |       |                           |
|--------------------|------------|-------|-------|-------|-------|------|-------|---------------------------|
| Element            |            | 3     | 4&16  | 5&14  | 7     | 12   | 13&15 |                           |
| Height             | $h$        | 720   | 1008  | 1202  | 770   | 580  | 1105  | mm                        |
| Width              | $b$        | 200   | 200   | 200   | 200   | 200  | 200   | mm                        |
| Area               | $A$        | 144   | 202   | 240   | 154   | 80   | 221   | $\cdot 10^3 \text{ mm}^2$ |
| Moment of inertia  | $I_y$      | 6221  | 17070 | 28940 | 7609  | 1067 | 22490 | $\cdot 10^6 \text{ mm}^4$ |
| Elastic modulus    | $W_{el,y}$ | 17280 | 33870 | 48160 | 19760 | 5333 | 40700 | $\cdot 10^3 \text{ mm}^3$ |

**Table F.11** Parameters in relation to the cross section for the beams.

The changed geometric parameters for the beams are shown in Table F.12.

| Geometry |     |      |      |      |      |      |      |      |
|----------|-----|------|------|------|------|------|------|------|
| Element  |     | 4    | 5    | 13   | 14   | 15   | 16   |      |
| Length   | $l$ | 2967 | 2950 | 2966 | 2967 | 2950 | 2950 | $mm$ |

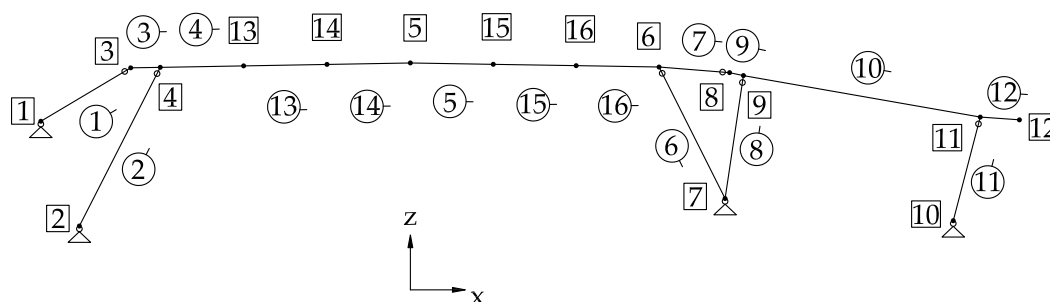
**Table F.12** Geometry parameters for the beams.

The changed load positions are shown in Table F.13.

| Load                  |          |   |          |
|-----------------------|----------|---|----------|
| Line load - magnitude | $p$      |   | 7.5 kN/m |
| Line load - position  | Elements | 1, 3, 4, 5, 7, 9, 10, 12, 13, 14, 15 and 16 | -        |
| Line load - magnitude | $q$      |   | 15 kN/m  |
| Line load - position  | Elements | 1, 3, 4, 5, 7, 9, 10, 12, 13, 14, 15 and 16 | -        |

**Table F.13** Load parameters.

For the timber frame structure the releases shown in Figure F.7 should be defined as shown in Table F.14.



**Figure F.7** The releases and supports for the timber frame structure.



| Boundary conditions   |       |       |       |       |       |       |
|-----------------------|-------|-------|-------|-------|-------|-------|
| <b>Element</b>        | 4     | 5     | 13    | 14    | 15    | 16    |
| <b>Start node</b>     | 4     | 5     | 13    | 14    | 15    | 16    |
| <b>End node</b>       | 13    | 15    | 14    | 5     | 16    | 6     |
| <b>Start releases</b> | Fixed | Fixed | Fixed | Fixed | Fixed | Fixed |
| <b>End releases</b>   | Fixed | Fixed | Fixed | Fixed | Fixed | Fixed |

**Table F.14** *Boundary conditions for the beams.*

## F.3 Procedure of tests

The procedure leading to the results in Table 4.1 are described in the following. The employed models can be found at the enclosed CD-ROM in the folder *4-TimberFrameStructure*.

### Revit add-on tool (RVT add-on)

The results in the add-on tool are obtained very easy.

- Revit Extensions, Simulation - Static Analysis of Frames:
  1. Delete supports from the steel columns.
  2. Calculations → Results (Only section forces, i.e. no code check is available.)

### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

To obtain the correct results in Robot some choices are necessary.

- Revit Extensions, Integration with Robot Structural Analysis (Send model):
  1. Choice about model correction in Robot
  2. Choice about bar end releases
  3. Choice about materials
- Robot:
  4. Verification → No errors and no warnings are found
  5. Redefine loads on element 12
  6. Redefine load combination (Type changed from dead load to snow load and from SLS to ULS)
  7. Calculation → Three irrelevant warnings → Results (Section forces and deflection.)
  8. Manually define element type as Timber column and Timber beam
  9. Define load duration
  10. Define service class
  11. Code check → Results (Section forces, deflection and code check.)

To update the model in Revit from the analysis in Robot, some choices are needed.

- Robot:

12. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  13. New code check
- Revit Extensions, Integration with Robot Structural Analysis (Update model):
    14. Choice about scope
    15. Nothing happens to the model in Revit except for when changing the section properties or material

### **Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)**

To obtain the correct results in StaadPro some choices and corrections are necessary.

- SI Xchange (Export):
  1. Choice about shape maps
  2. Choice about units
- StaadPro:
  3. Manually define cross sections
  4. Redefine loads on element 10 and 12 (the position of the load on element 10 wrong and the load on element 12 is missing)
  5. Manually add self weight
  6. Choose type of analysis (Analysis/Print: All, Design - Timber: EC5 (define load duration, member type and section class))  
→ Results (Section forces, deflection and code check.)

Note: Coordinate system different from Robot.

To update the model in Revit from the analysis in StaadPro, some choices are needed.

- StaadPro:
  7. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  8. New code check
- SI Xchange (Import):
  9. Nothing happens to the model in Revit

## Three-dimensional steel structure

---

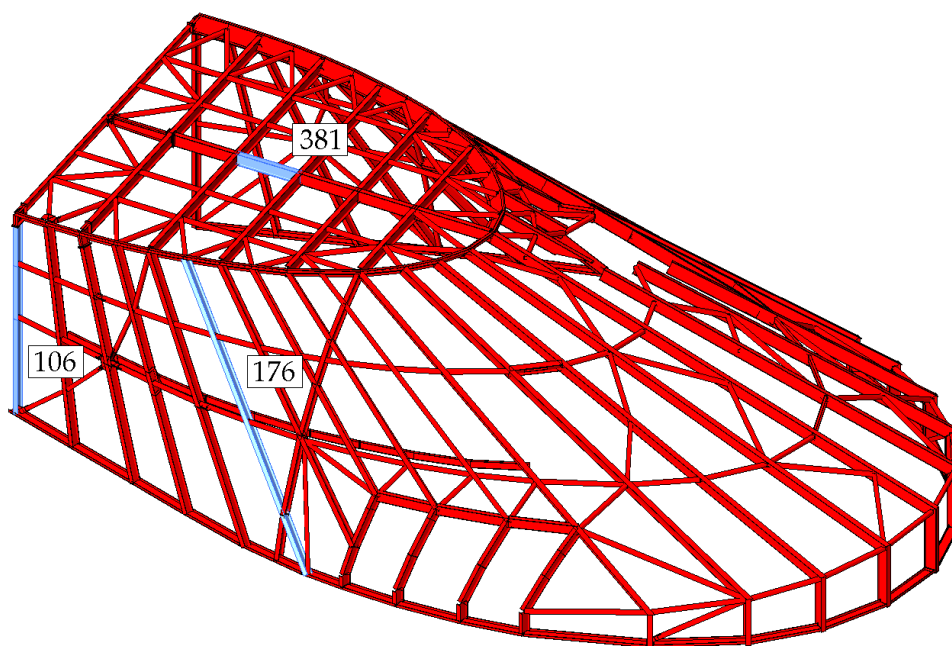
The design parameters and procedure described in this appendix form the basis of the tests performed in Chapter 5.

---

### G.1 Design parameters

The parameters needed to evaluate the design criteria in Section 5.3 are presented in the following tables.

The three-dimensional steel structure is shown in Figure G.1.



**Figure G.1** *The three-dimensional steel structure and the elements selected for code check.*

The parameters related to the cross section of the selected elements are shown in Table G.1.

| Section properties |            |        |        |        |                           |
|--------------------|------------|--------|--------|--------|---------------------------|
| Element            |            | 106    | 176    | 381    |                           |
| Profile            |            | IPE400 | IPE400 | IPE500 |                           |
| Section class      |            | 1      | 1      | 1      |                           |
| Height             | $h$        | 400    | 400    | 500    | mm                        |
| Width              | $b$        | 180    | 180    | 200    | mm                        |
| Web thickness      | $t_w$      | 8.60   | 8.60   | 10.2   | mm                        |
| Flange thickness   | $t_f$      | 13.6   | 13.6   | 16.0   | mm                        |
| Radius             | $r$        | 21.0   | 21.0   | 21.0   | mm                        |
| Area               | $A$        | 8.45   | 8.45   | 11.6   | $\cdot 10^3 \text{ mm}^2$ |
| Moment of inertia  | $I_y$      | 231    | 231    | 482    | $\cdot 10^6 \text{ mm}^4$ |
| Moment of inertia  | $I_z$      | 13.2   | 13.2   | 21.4   | $\cdot 10^6 \text{ mm}^4$ |
| Torsion constant   | $I_t$      | 514    | 514    | 897    | $\cdot 10^3 \text{ mm}^4$ |
| Warping constant   | $I_w$      | 490    | 490    | 1250   | $\cdot 10^9 \text{ mm}^6$ |
| Plastic modulus    | $W_{pl,y}$ | 1.31   | 1.31   | 2.19   | $\cdot 10^6 \text{ mm}^3$ |
| Plastic modulus    | $W_{pl,z}$ | 0.23   | 0.23   | 0.34   | $\cdot 10^6 \text{ mm}^3$ |

Table G.1 Parameters in relation to the cross section for the selected elements.

The relevant geometric parameters for the beams and columns are shown in Table G.2. The effective length is equal to the length of the elements. This is not necessarily correct but maintained since it is default in Robot and StaadPro. Furthermore it is not relevant for the tests.

| Geometry         |           |      |       |      |    |
|------------------|-----------|------|-------|------|----|
| Element          |           | 106  | 176   | 381  |    |
| Length           | $l$       | 8895 | 12551 | 2581 | mm |
| Effective length | $l_{eff}$ | 8895 | 12551 | 2581 | mm |

Table G.2 Geometry parameters for the selected elements.

The parameters that define the material steel S355 are presented in Table G.3.

| Material properties   |        |       |                   |  |
|-----------------------|--------|-------|-------------------|--|
| Yield stress          | $f_y$  | 355   | MPa               |  |
| Modulus of elasticity | $E$    | 210   | GPa               |  |
| Shear modulus         | $G$    | 81    | GPa               |  |
| Density               | $\rho$ | 77.01 | kN/m <sup>3</sup> |  |

Table G.3 Material parameters.

As described in Section 5.3 the structure is subjected to self weight and snow load in addition to the self weight of the steel. The loads are shown in Table G.4. The area loads are modelled as line loads with varying magnitude according to the varying load areas.

| Loads              |       |      |                   |
|--------------------|-------|------|-------------------|
| Area load - Roof   | $g_r$ | 2.0  | kN/m <sup>2</sup> |
| Area load - Facade | $g_f$ | 1.5  | kN/m <sup>2</sup> |
| Area load - Roof   | $s_r$ | 0.72 | kN/m <sup>2</sup> |
| Area load - Facade | $s_f$ | 0.72 | kN/m <sup>2</sup> |

Table G.4 Load parameters.

For the three-dimensional steel structure the columns are generally pinned in the bottom. The releases and supports for the selected elements are shown in Table G.5.

| Boundary conditions |         |         |         |
|---------------------|---------|---------|---------|
| Element             | 106     | 176     | 381     |
| Start node          | 164     | 153     | 254     |
| End node            | 167     | 26      | 256     |
| Start releases      | xxxxxxx | xxxxxxx | xxxxfxf |
| End releases        | xxxxxxx | xxxxxf  | xxxxfxf |
| Support             | xxxfff  | xxxfff  | -       |

Table G.5 Boundary conditions for the selected elements.

To be able to assess the design criteria the applied applications must be able to find the parameters given in Table G.6.

| Design data             |              |      |      |      |                 |
|-------------------------|--------------|------|------|------|-----------------|
| Element                 |              | 106  | 176  | 381  |                 |
| Moment capacity         | $M_{pl,y,R}$ | 422  | 422  | 708  | kNm             |
|                         | $M_{pl,z,R}$ | 73.9 | 73.9 | 108  | kNm             |
| Reduced moment capacity | $M_{N,y,R}$  | 422  | 422  | -    | kNm             |
|                         | $M_{N,z,R}$  | 73.9 | 73.9 | -    | kNm             |
| Shear capacity          | $V_{pl,R}$   | 795  | -    | 1125 | kN              |
|                         | $V_{pl,T,R}$ | -    | 795  | -    | kN              |
| Normal capacity         | $N_{pl,R}$   | 2.73 | 2.73 | 3.74 | $\cdot 10^3$ kN |
|                         | $N_{cr,y}$   | 6.06 | 3.04 | 150  | $\cdot 10^3$ kN |
|                         | $N_{cr,z}$   | 0.35 | 0.17 | 6.66 | $\cdot 10^3$ kN |

Table G.6 Parameters in relation to design of the selected elements.

The section forces in the selected steel elements are shown in Table G.7.

| Results            |           |      |      |      |     |
|--------------------|-----------|------|------|------|-----|
| Element            |           | 106  | 176  | 381  |     |
| Length of elements |           | 8.9  | 12.6 | 2.6  | m   |
| Point for results  |           | 6.5  | 3.3  | 0    | m   |
| Normal force       | $N_E$     | 48.6 | 3.3  | 23.2 | kN  |
| Bending moment     | $M_{y,E}$ | 43.0 | 57.4 | 38.5 | kNm |
|                    | $M_{z,E}$ | 0.44 | 0.4  | -    | kNm |
| Shear force        | $V_{y,E}$ | 0.33 | 2.22 | -    | kN  |
|                    | $V_{z,E}$ | 6.58 | 19.0 | 13.8 | kN  |
| Torsional moment   | $T_{t,E}$ | -    | 0.01 | -    | kN  |

Table G.7 Results of calculations for the steel structure.

The results obtained according to the design criteria in Section 5.3 are shown in Table G.8.

| Results     |   |      |      |      |  |
|-------------|---|------|------|------|--|
| Element     |   | 106  | 176  | 381  |  |
| EC3 6.2.5   | $\left(\frac{M_{y,E}}{M_{N,y,R}}\right)^\alpha + \left(\frac{M_{z,E}}{M_{N,z,R}}\right)^\beta$                              | 0.11 | 0.14 | 0.05 |  |
| EC3 6.2.6   | $\frac{V_E}{V_{c,R}}$   | 0.01 | -    | 0.01 |  |
| EC3 6.2.6-7 | $\frac{V_E}{V_{pl,T,R}}$  | -    | 0.02 | -    |  |
| EC3 6.3.3   | $\frac{N_E}{\chi_y \cdot N_{pl,R}} + k_{yy} \frac{M_{y,E}}{\chi_{LT} \cdot M_{pl,y,R}} + k_{yz} \frac{M_{z,E}}{M_{pl,z,R}}$ | 0.15 | 0.09 | 0.06 |  |
|             | $\frac{N_E}{\chi_z \cdot N_{pl,R}} + k_{zy} \frac{M_{y,E}}{\chi_{LT} \cdot M_{pl,y,R}} + k_{zz} \frac{M_{z,E}}{M_{pl,z,R}}$ | 0.25 | 0.10 | 0.01 |  |

Table G.8 Results of calculations for the steel structure.

## G.2 Procedure of tests for import to Revit from Tekla Structures

The procedures for import of the three-dimensional steel structure in Revit are described in the following. The employed models can be found at the enclosed CD-ROM in the folder 5-*ImportFilesRevit*.

### Import to Revit via a DWG file (Tekla $\xrightarrow{\text{DWG}}$ RVT)

There are two different methods of importing the DWG file in Revit. The procedure is the same.

- Import CAD or Link CAD:
  1. The structure appears as one object in Revit
  2. Each element consists of lines i.e. it is not an object and has no analytical representation

### Import to Revit via an IFC file (Tekla $\xrightarrow{\text{IFC}}$ RVT)

The procedure of importing the IFC file.

- Open IFC:
  1. Two errors (Can't keep elements joined and can't regenerate IPE400)  
→ Unjoin elements
  2. Each element is an object but has no analytical representation

### Import to Revit via a CIS/2 file (Tekla $\xrightarrow{\text{CIS/2}}$ RVT)

The procedure of importing the CIS/2 file.

- Add-on - CIS/2 Import:
  1. Choice about model: Analytical model (324 elements)
  2. Two irrelevant warnings about some concrete elements that do not exist in the model
  3. 132 imported elements and 192 unimported elements (166 of them are SHS elements)
  4. Three errors (Can't keep elements joined and can't make IPE400)
  5. Eight warnings (Beam or brace is slightly off axis and may cause inaccuracies)  
→ Unjoin elements
  6. One error (Can't make IPE400) → Delete type
  7. Each element is an object with an analytical representation

### G.3 Procedure of tests

The procedure leading to the results in Table 5.2 are described in the following. The employed models can be found at the enclosed CD-ROM in the folder *5-Three-dimensionalSteelStructure*.

#### Revit add-on tool (RVT add-on)

It is easy to use the add-on tool, however it is only possible to handle one element at a time.

- Revit Extensions, Simulation - Static Analysis of Frames:
  1. Delete supports added in every node point along the element
  2. Calculations → Results (The results are wrong since loads from the adjacent elements are not taken into account.)

#### Direct link from Revit to Robot and backwards (RVT ↔ RSA)

To obtain results in Robot some choices are necessary.

- Revit Extensions, Integration with Robot Structural Analysis (Send model):
  1. Choice about model correction in Robot
  2. Choice about bar end releases
  3. Choice about materials
- Robot:
  4. Verification → One irrelevant warning is found
  5. Manually define element types as Simple bar
  6. Calculation → One irrelevant warning → Results (Section forces and deflection.)
  7. Code check → Results (Section forces, deflection and code check.)

To update the model in Revit from the analysis in Robot, some choices are needed.

- Robot:
  8. Update section properties, geometry, material properties, loads and boundary conditions one at a time
  9. New code check
- Revit Extensions, Integration with Robot Structural Analysis (Update model):
  10. Choice about scope
  11. Nothing happens to the model in Revit except for when changing the section properties

#### Direct link from Revit to StaadPro and backwards (RVT ↔ SPro)

To obtain results in StaadPro some choices and corrections are necessary.

- SI Xchange (Export):
  1. Choice about shape maps



#### 2. Choice about units

- StaadPro:

3. Redefine BC's
4. Redefine releases since the y and z coordinate is changed
5. Manually define cross sections and add them to the elements (Relevant for the elements with square hollow sections)
6. Redefine loads at three elements where the loads are missing
7. Manually add self weight
8. Choose type of analysis (Analysis/Print: All, Design - Steel: EC3)  
→ Results (Section forces, deflection and code check.)

Note: Coordinate system different from Robot.

To update the model in Revit from the analysis in StaadPro, some choices are needed.

- StaadPro:

9. Update section properties, geometry, material properties, loads and boundary conditions one at a time
10. New code check

- SI Xchange (Import):

11. Nothing happens to the model in Revit except for when changing the section properties