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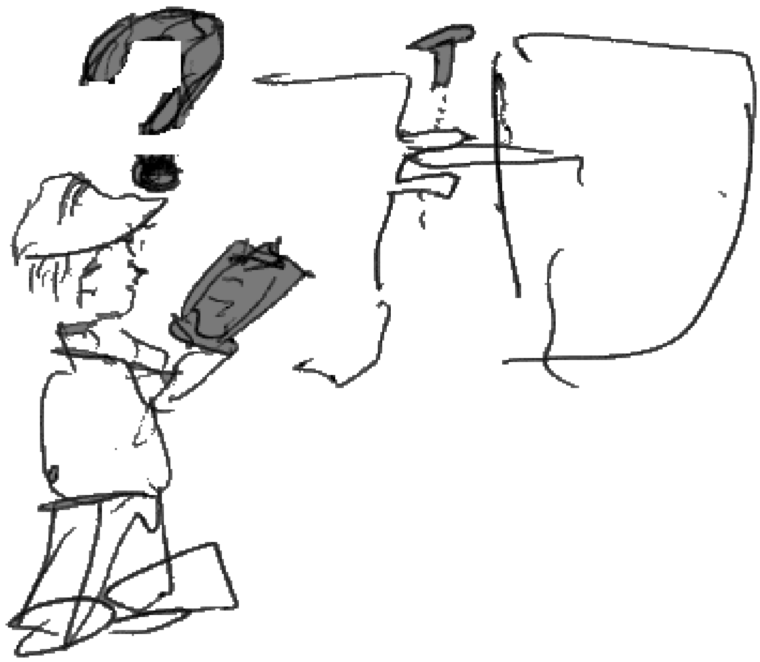

Connection Design for Easy Assembly On-Site

Method to Design and Evaluate Structural Connections in Industrial Construction

Master's Thesis in the International Master's programme Structural Engineering

ERIK JÜRISOO

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Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2007

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Cover:
Designer evaluating a structural connection regarding assemblability using the developed design method.

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ABSTRACT

Today, on-site production is a common construction technique in building industry, which can be inefficient regarding cost and production time. Therefore an industrial construction process is needed. Building industry should both be flexible in order to meat the users' demands and at the same time keep a low production cost. Knowledge could be gained from manufacturing industry which, during a long tradition of industrial processes, has developed several design methods in order to standardise the way of thinking. This master's project concerns connection design with focus on assembly, therefore methods concerning assembly were studied in order to see if they could be adjusted and used in building industry. In addition to the methods, guidelines from building industry were investigated. An obvious difference between manufacturing industry and building industry is the size of products and parts; the whole assembly will be larger in building industry. Production in manufacturing industry is also performed in a suited location, which is unusual for building construction.

During the study, different demands on design methods were found; a design method should for instance be complete, systematic, measurable and user-friendly. With the knowledge from the studies, a four step iterative design method for structural connections in industrial construction was developed. The method starts with guidelines aimed to help the designer develop connections which are easy to assemble. Next, design proposals, which should be investigated with help of the method, have to be described with comments and figures. Then absolute demands, depending on the design situation, are controlled using a checklist. A connection must for example withstand design loads. The next step is an evaluation regarding the connections' assemblability, consisting of criteria divided into three statements. A grade is calculated for each criterion depending on the studied connection's performance and the criterion's importance. The result of the evaluation is a mean grade and an assembly index for each connection. A case study has been performed in order to improve the method and it has shown that the evaluation method works satisfactory. The last step of the method concerns reduction of unnecessary parts. When using the design method an iterative procedure is recommended.

It is important to stress that assemblability is one aspect among many which have to be considered during a design process. However, assembly has a major impact on the total production process and was therefore chosen to be the focus in this project.

Key words: structural connection, industrial construction, building industry, design for assembly (DFA), easy assembly, design method, evaluation, guidelines

Anslutningsutformning för enkelt montage
Metod för utformning och utvärdering av kraftöverförande anslutningar i industriellt byggande
Examensarbete inom International Master's Programme in Structural Engineering
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Chalmers tekniska högskola

SAMMANFATTNING

Platsbyggnation används idag i stor utsträckning inom byggindustrin men processen kan vara ineffektiv ur ett kostnads- och produktionstidsperspektiv. En industriell byggprocess kan vara en möjlig lösning. För att uppfylla kundernas krav och samtidigt hålla en låg produktionskostnad behöver byggprocessen vara flexibel. Tillverkningsindustrin har en lång tradition av industriella processer och har därigenom utvecklat flera designmetoder med mål att få en standardiserad tankeprocess. Detta examensarbete behandlar anslutningsutformning med inriktning på enkelt montage. Därför har designmetoder som behandlar detta ämne studerats för att undersöka om de kan anpassas för användning inom byggindustrin. Utöver dessa metoder har även riktlinjer från byggindustrin studerats. En uppenbar skillnad mellan tillverkningsindustrin och byggindustrin är storleken på produkter och delar. Hela montaget tenderar att vara större inom byggindustrin. Dessutom utförs produktionen i tillverkningsindustrin i en väl anpassad miljö vilket är ovanligt i byggindustrin.

Studien resulterade bland annat i krav som visar att en designmetod ska vara komplett, systematisk, mätbar och användarvänlig. En designmetod för kraftöverförande anslutningar i industriellt byggande har utvecklats med utgångspunkt från studien. Metoden är uppdelad i fyra steg och börjar med riktlinjer för utformning av anslutningar som är enkla att montera. Anslutningsförslagen som ska utvärderas med hjälp av metoden måste förklaras med figurer och text. För att säkerställa att anslutningen exempelvis klarar att ta upp dimensionerande last kontrolleras absoluta krav med en checklista. Nästa steg i metoden är en utvärdering av anslutningarnas montagevänlighet. Utvärderingen är baserad på kriterier som är uppdelade i tre påståenden. Ett betyg sätts på varje kriterium beroende både på anslutningens egenskaper och på kriteriets relevans. Resultat av utvärderingen är ett medelbetyg samt ett montageindex för varje anslutning. Utvärderingsmetoden har förbättrats och säkerställts med hjälp av en fallstudie. Slutligen minimeras antalet delar genom en frågeprocedur. Design med metoden bör ske iterativt.

Det är viktigt att poängtera att montaget är en av flera aspekter som måste tas hänsyn till i en designprocess. Detta projekt fokuserar dock på montaget eftersom det har stor betydelse för byggprocessen.

Nyckelord: kraftöverförande anslutningar, industriellt byggande, monteringsvänlig utformning (DFA), enkelt montage, design metod, utvärdering, riktlinjer

Contents

Preface

This master's project was carried out at NCC Teknik, Sweden, and at the Division of Structural Engineering at Chalmers University of Technology, Sweden, during the summer of 2007.

We would like to start with big thanks to our supervisors at NCC Teknik, Dr Jonas Magnusson and Adj. Prof. Dan Engström, for their help during the whole project. They have been a great support for us and have always been available for questions and discussions. We would also like to thank our supervisor and examiner Björn Engström, professor in Concrete Structures at the Department of Civil and Environmental Engineering, for valuable input during the project. Furthermore, we would like to give our gratitude to the entire staff at NCC Teknik, Göteborg, for providing a good working climate. Special thanks to Anna Holmstöm, Martin Sandén and Niklas Sparw for their support in specific questions.

During the project, we have been six students working in a small office room with three different master's projects. Therefore, special thanks must be sent to Rickard Caster, Gustav Deuschl, Carl Jansson and Sven Tägtsten for creating a joyful working environment. Carl and Sven have also been our opponents and therefore they deserve extra thanks for valuable proofreading and support.

Finally, we would also like to thank our fiancées Madeléne Emriksson and Veronica Dahlgren for encouragement and support.

Göteborg, September 2007

Erik Jürisoo & Robert Staaf

Notations

Below, all variables occurring in the report (text, equations, figures and tables) are listed in alphabetically order:

A	Assembly index
E	Assembly evaluation score ratio
E_a	Assembly efficiency
E_d	Design efficiency
G	Criteria grade
I	Importance factor
I_f	Fitting index
I_h	Handling index
K	Assembly cost ratio
n	Number of parts
n_A	Number of essential parts
$n_{\min}$	Theoretical minimum number of parts
P_s	Penalty score
p	Statement point
t_{acq}	Tool acquisition time
t_{ba}	Basic assembly time for one part
t_{ea}	Estimated assembly time
t_h	Time for handling
t_{in}	Time for insertion
t_{ta}	Total assembly time
α	Rotation angle, rotation perpendicular to the axis of insertion
β	Rotation angle, rotation around the axis of insertion

1 Introduction

In this chapter a short introduction of industrial construction is given, including needs for development of the building industry. This is followed by aim, method and limitations of this master's project.

1.1 Building Industry and Industrial Construction

Today, on-site production is a common construction technique in building industry, which may be inefficient with regard to cost and production time. Many hours are consumed in the construction process, where problems often appear and are solved on-site. Those problems are reasons why a change is needed. An industrial construction process might solve some of these problems. When a building consists of prefabricated elements, the production time can be reduced. In this case most of the time consumed at the construction site is spent on assembly and supplementary work. If the building elements, on the other hand, are complete at delivery the main activity at the construction site will be to assemble the complete elements. In this way, no or only some complementary work will be needed, which is a desirable goal in industrial construction.

Several definitions of industrial construction are possible; the one chosen in this project is as follows: "Industrial construction refers to an integrated manufacturing and construction process with a well-designed organisation which comprises effective steering, preparation and control of the resources, activities and results with the help of highly refined components." This definition is stated by Lessing *et al.* (2005), with translation according to Lassl and Löfgren (2006). In industrial construction more time is spent on project planning in order to reduce the time needed for assembly and supplementary work, which is schematically illustrated in Figure 1.1. The time consumed for foundation work will still be approximately the same. Industrial construction is discussed by Engström and Claesson-Johnsson (2005) who stresses that an industrial construction process gives many benefits compared to an ordinary building process, for example a decrease of the total construction time. Easy assembly, which is studied in this project, is only one of several aspects that are important to consider in industrial construction. Cost and quality are examples of other aspects that must be considered in the design phase. Moreover, industrial production can result in improved working conditions of the workers as many of the steps of a construction process are handled inside a factory where working positions and climate can be adjusted for better ergonomics and working environment.

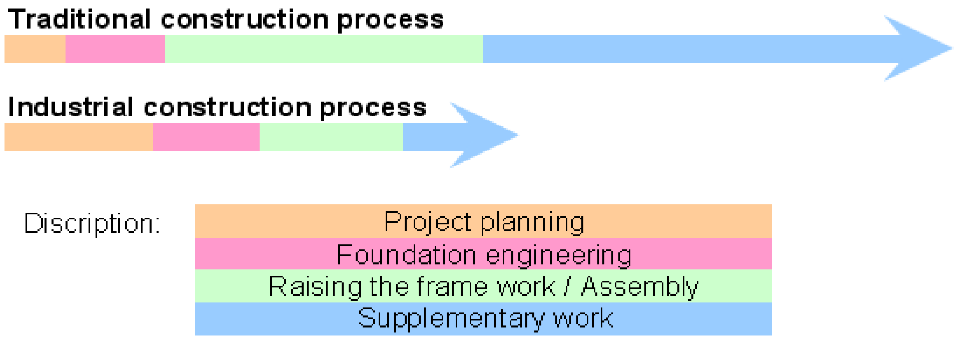


Figure 1.1 Possible difference between traditional and industrial construction process.

The industrial construction of today should not be compared with the post-war mass housing. These houses were mass produced with high standardisation of elements and low flexibility and are often considered as houses with a low value regarding living environment and aesthetics. Modern industrial construction must therefore be flexible in order to meet the users' demands and at the same time keep a low production cost. Questions concerning industrial construction are currently discussed in building industry. In a European research initiative, ManuBuild (www.manubuild.org), there is an ongoing discussion concerning open building systems. In an open building system several actors have the opportunity to develop components to the system, which is not the case in a closed system were only the system owner handles the development. The open building system is rather a vision than a solution. It might not be possible to have only one compatible open system, it may not even be desired. Engström and Johansson (2007) discuss that the focus should rather be on the process than on the product. The working process may be standardised; a high standardisation of design methods has the aim to keep the production costs as low as possible.

1.2 Design Methods

Various design methods in different industries have been developed in order to standardise the design process. These methods can be described as Design For X (DFX) methods where X can be replaced with, for instance, assembly which is treated in this master's project. Every DFX method is developed to fit the specific demands and needs in a specific application. Some DFX methods are well developed, using computer systems in the design process. Manufacturing industry has a long tradition of design methods in opposite to building industry where no such design method exists. If a transition from traditional construction techniques to industrial construction techniques is desired, an appropriate design method has to be developed. A design method can focus on the whole product or only on some few parts. For instance, a method can consider the structural connections between the different elements that form a building.

Connections are important parts of a building with regard to assembly time and cost. When designing a connection it is important to consider different demands. A structural connection should for instance be able to withstand all actions subjected to it and fit into its environment; it should also be durable and of low cost. Further on, the design has to be done according to current design codes. The result of the design process is often a compromise between several demands and requirements.

1.3 Aim of the Master's Project

To get a more efficient building industry, this Master's project aims to suggest a method of how to design and evaluate structural connections in building structures which makes elements easier to assemble. The aim can be divided into two parts as follows below.

Firstly, the aim is to analyze design methods used in manufacturing industry. These methods should be studied in order to find out if they are applicable in building industry or difficult to use. If possible, potential needs for improvement should be identified and described. Also guidelines from building industry should be examined in order to adopt useful information.

Secondly, the aim is to adopt the studied techniques and methods used in manufacturing industry and adjust them to a design and evaluation method for structural connections in industrial construction. When the method is developed, the special needs of building industry should be considered. The final method should consider development and evaluation of structural connections. When using the method, studied connections should be compared and possible areas for improvement should be identified.

In order to make the content more clear, the aim described above can be presented in two short notations:

- Investigate potential design methods in manufacturing industry and guidelines used in building industry. Identify their need for improvement in order to match connection design in industrial construction.

- Develop a design and evaluation method for structural connections in industrial construction, including case study verification.

1.4 Method

In order to achieve the aim of this master's project and get a theoretical knowledge of the subject, literature studies were performed. Moreover, visits were made at building sites and at a production line at a car manufacturer in order to get more understanding of the present situation in building industry and manufacturing industry. The theoretical knowledge, gained in the studies, was then used to develop a design method for connections used in building industry with focus on assembly. The design method was checked, calibrated and improved with help of a case study.

The master's project is partly based on the previous master's thesis, *Smart connection development for industrial construction*, written by Lassl and Löfgren (2006).

1.5 Limitations

The master's project handles structural connection design only, but the developed method presented in the thesis can be adapted to other design situations in building industry. The design concerns the product development stage, i.e. the development of a building system, and not the development of a specific project where the system is adjusted to meet certain demands. The method focuses on assembly on site where most of the economical savings can be made; assemblies that are performed in a factory are not considered.

1.6 Outline of the Thesis

Below, the content of the following chapters are described.

Chapter 2 starts discussing the structural behaviour of building systems followed by defining connections and their demands. Demands on industrial construction are also treated.

In Chapter 3 several design methods are identified and described. There are both methods containing only guidelines and methods that also estimate the time consumed or the cost for a certain assembly.

An analysis of the described design methods is presented in Chapter 4. Here the similarities and differences of the methods are explained. The need for improvement in order to make the methods suitable for connection design in building industry is discussed. Also the differences between manufacturing industry and building industry are handled.

Chapter 5 describes requirements on design methods in general followed by a presentation of a proposed design method for structural connections. The method contains four steps; general guidelines, a checklist with regard to absolute demands, an evaluation method of easy assembly and a technique to minimise the number of parts in the studied connection.

The case study, which is described in Chapter 6, was performed in order to improve the method. All connections tested in the case study are presented as well as the general results. Further on, some rejected parts of the design method are presented and the further development of the design method is described.

In Chapter 7 conclusions of the project are presented. The result is compared to the aim of the master's project and suggestions for further studies are pointed out.

In Appendix A all four parts of the final design method are presented as work sheets.

Appendix B contains the case study with detailed results from all the studied connections.

2 Structural Connections

The chapter begins with a definition of structural connections, followed by a presentation of demands that the connections must fulfil, generally taken from Betongvaruindustrin (2005).

2.1 Definition of Structural Connections

In order to develop a method for connection design and evaluation, it is necessary to define the connections. They can be defined in many different ways. It could for instance be defined as just a dowel, connecting two elements. However, in this project a structural connection is defined as the zone where two or more parts of a building meet, attach and join. A connection includes the influenced parts of the elements to be assembled, for example the part of a concrete element that is influenced by the reaction forces from a concentrated bearing. This definition is chosen in order to see the connections in an overall context.

2.2 Demands on Structural Connections

When designing a structural connection it is important to consider several demands. Industrial construction results in new demands on the building process since each building then consists of several prefabricated elements. All elements should be tied together using structural connections instead of being constructed as a single unit, see Figure 2.1.

Even though this project focus on methods for easy assembly, it is important to point out some other demands that need to be considered when designing a connection. Demands regarding the whole building structure can often be transformed to demands concerning the connections. The demands have in this project been divided into three categories; load-bearing capacity, serviceability and sustainability. However, this section starts discussing structural behaviour in general.

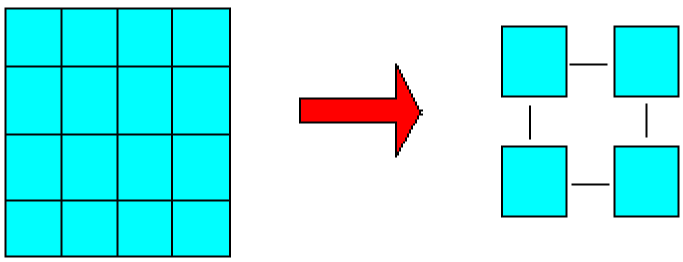


Figure 2.1 In industrial construction, buildings consist of prefabricated elements that has to be tied together using structural connections.

2.2.1 Structural Behaviour

Different actions that will give rise to loads or in other ways affect the structure during its service life are important to identify. The following text will therefore discuss some of these actions.

When a connection should be designed, it is necessary to decide which loads that should be transferred and which forces that may arise in the connection. It has to be decided how alternative connection designs withstand these actions. Forces and movements are a result of for example imposed loads, loads from snow, wind, creep, shrinkage, temperature changes, variations in relative humidity, and settlement. All these influences affect the need for strength and movements in connections. A frame work, for example, and its connections, must either have some ability to move or to be able to resist restraint forces that will appear. If not, the connections or the element will be damaged or, in worse case, fail.

Connections and elements should have an ability to move and deform, as discussed above. Connections must, however, be designed to keep the deflections at an acceptable level in the service state. Deflection mainly depends on the stiffness of the elements, but in some cases deflection has to be considered in the connection design. Deflection is often not decisive for failure; it is then limited by the users' opinion of which level of deflection that is acceptable. Also the thermal elongation of members has to be considered, as this result in restraint forces and/or need for movement. For this reason, connections should for example be able to resist or be protected against fire without loss of strength. This can be extra important for some materials, e.g. steel, which can easily be weakened by fire.

A connection can be able to both deform to some extent and at the same time resist some restraint forces, as the connections can be designed to be partly restrained. In this case the connection deforms when load is applied, so that the restraint forces decrease. As an example a connection that is designed to be simply supported can, under certain circumstances, function as partly fixed. This is the case when a floor element is placed between the upper and the lower wall. Before the upper wall is connected, the floor element will be simply supported, but as soon as the wall is in place there might be a bending moment due to the fixation. Due to this moment, there might be unintended tensile stresses in the top of the floor element. The behaviour can thus be different for assembly, normal use, extreme loads and long term loading.

Additionally, all connections should have a ductile behaviour, i.e. be able to have large plastic deformations before rupture. This is important to consider for example for a system of columns. Even if a column is damaged the floor above should not collapse. The connections have to withstand the loads despite large deformations and they should not have a brittle behaviour.

2.2.2 Load-Bearing Capacity

The most obvious demand is the load bearing capacity, i.e. the connection has to be able to transfer the design actions. There may be different types of load at different stages, i.e. during construction, during the service life and at possible accidents. A connection has to resist the design loads at all stages. Even if an element fails, its connections must be strong enough to hold the rest of the elements together preventing a progressive collapse. The loads acting on a connection at collapse can accordingly be completely different from the loads in the ordinary design situation. There can be several types of forces affecting a connection. It should be able to withstand tension, compression, shear or bending moment, or a combination of two or more of these forces. Each will be presented below.

Compressive force: The most common way to transfer compressive forces between elements is by simply placing one element on top of another. It is important that the compression stresses are spread evenly over an area, else concentrated forces will arise. It is also important to investigate the effect of local compressive forces under concentrated loads. This is extra important regarding timber structures where compressive forces perpendicular to the grain can be dangerous due to the low strength in this direction, and for concrete structures where splitting effects may cause cracking.

Tensile force: Regarding tensile force capacity, there is a large difference between different building materials. Concrete does, for example, not have very high tensile strength, and it is therefore important that the tensile force is transferred through the connections to the reinforcement in the members. The reinforcement bars also have to be anchored properly. The anchorage capacity depends on the surface of the bar, the strength of the concrete and the anchorage length. As steel bars usually are used as reinforcement in concrete structures, it is understandable that steel has a high tensile capacity. Another beneficial property of steel is that the tensile capacity is equal in all directions. This is not the case for wood based materials, as timber beams, where the tensile capacity can differ depending on if the load is applied perpendicular or parallel to the grain.

Shear force: In some cases, e.g. in concrete structures, friction between elements or connection details can be used to resist shear. With rough surfaces there will naturally be a shear resistance if there is a compressive force or reinforcement perpendicular to the surface preventing the surfaces from moving apart, see Figure 2.2. If a dowel is used to resist shear, splitting has to be considered. The dowels should not be placed too close to a free edge. Possible splitting patterns can be seen in Figure 2.3. In industrial construction, it is important to be able to transfer shear forces between elements and from elements to the foundation, illustrated in Figure 2.4. This sets extra demands on the connections which might need to transfer the force through small areas.

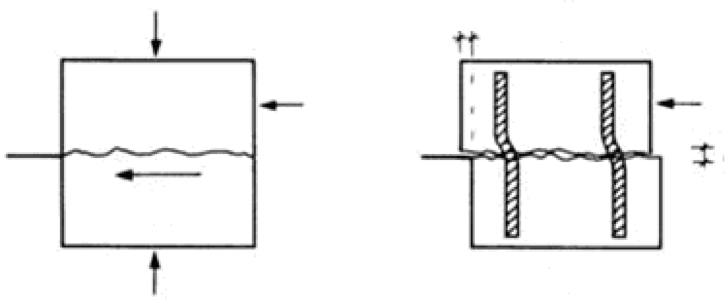


Figure 2.2 *Friction can resist shear when compression is applied perpendicular to the surfaces or when the pullout resistance of pullout tie bars is activated by the shear displacement, from Betongelement-föreningen (2000).*

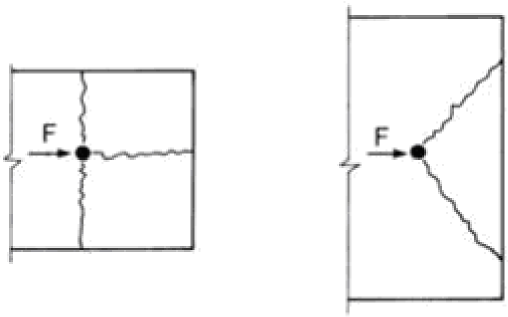


Figure 2.3 *Possible splitting modes for a dowel close to a free concrete edge, from Betongelementföreningen (2000).*

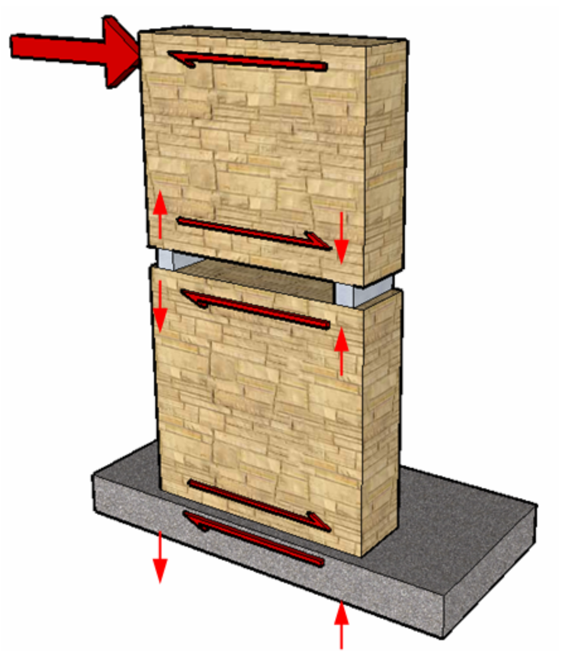


Figure 2.4 *Forces between elements.*

Bending moment: Moment resisting connections can be used to stabilise elements and buildings. The requirements on such connections are often harder and the connections can be more complex. One way to make a moment resisting connection less complex is to use interaction between two or more force transfer mechanisms, since bending can be a combination of tensile and compressive forces both effects has to be considered in design.

2.2.3 Serviceability

The connections must function satisfactory during its service life and have acceptable appearance. Below some aspects will be discussed.

Appearance

The appearance of a building or connection is hard to grade since there exist no definitive guidelines regarding this subject. The opinion of beauty is individual and depends on the observers' point of view, culture and fashion. It is also important to note that the observers can change their definition of beauty over time and therefore even their opinion of appearance. Appearance can be called a soft requirement, which is difficult to quantify.

Visible connection details are often undesired; they are preferred to be hidden. The user, of for example an apartment, should not have to see connection details between building elements. If a connection detail on the other hand is visible, it can be designed to either be a part of the architecture or blend into the structure, according to *fib* (2007). If engineers and architects cooperate, a building structure can be formed as an aesthetic expression. This is called tectonic architecture which is important also for connection design. Aesthetic design and its technical and structural consequences are not treated further in this project but are discussed by Engström *et al.* (2004).

Building Performance

Connections have to be tight for many reasons, e.g. transport of water, moisture and air. These transports must be prevented to avoid damages of the building and problems with indoor climate. Leakage can be a problem regarding ventilation; the ventilation system might be disturbed and malfunction if the building is not tight enough. Heat can also be transported through sections that are not sufficiently tight. It is also important to consider the risk of thermal bridges and the connections need to be designed to avoid these. This can be a problem in an energy point of view, as major heat leakage can result in unnecessarily large energy consumption. Furthermore, sound and vibration can give an unpleasant environment for the users of a building. The disturbance often comes from the surrounding environment as traffic or neighbours. The connection, that often is the decisive part of the structural system, has to be designed tight in order to ensure the building environment with regard to sound and vibration.

Tolerances

One of the most difficult issues in industrial construction concerns tolerances. Naturally, the elements to be assembled, and their connections, have to be designed with a predefined tolerance. A narrow tolerance might be necessary in order to make the elements and the connections fit together but a narrow tolerance is however also more expensive. When it is not necessary to have a tight tolerance, a more generous one should be used. It is important to define the tolerances that are acceptable for an element and its connections. If the part to be assembled is not manufactured accurately it might be impossible to put it into place and to use the connections as intended. Connections must have a design that allows deviations within specific tolerances. Too small tolerances are not good regarding connection design.

Problems with tolerances are further discussed in a report by Linda Mattsson (2005). The author compares tolerances in building industry with tolerances in car industry. Undoubtedly, many building materials expand or in other way change in size which results in a need for larger tolerances in building industry than in car industry. Furthermore, there are generally two ways to handle tolerances. Firstly, size deviations can be taken by the last connection in e.g. a row of wall elements or, secondly, the deviations can be taken by every connection between the elements so they align with the elements underneath and above. The choice of solution depends on the current system.

2.2.4 Sustainability

One important part of sustainability is durability. The connection should be able to perform and fulfil its purpose during its service life. Therefore, it is important to have knowledge about the environmental conditions that the connections are exposed to. Different environmental conditions affect the structure in different ways and in different amounts. In order to make sure that a connection works correctly during its service life, maintenance might be needed. It is important that the design process includes maintenance. The cost for i.e. material in connections must be compared with the cost for maintenance during its service life. If maintenance is necessary, it should be easy to perform. Furthermore, the connection should not be too hard to access. No connections should need repair, only planned maintenance.

Additionally, buildings, including their connections, should affect the environment as little as possible during its lifetime. It should be effective with regard to material use, but also designed in such a way that deconstruction and recycling are easy to perform. It is preferred that buildings are demounted instead of demolished and for this reason the structural connections are important.

3 Identification of Design Methods and Guidelines

In this chapter design methods are identified and summarized. All methods treated concern the assembly because this is a potential cost saver in building industry. However, the first section handles general information of design methods.

3.1 Design Methods

As introduced in Chapter 1, there exist several different design methods in the manufacturing industry. The design methods can be developed for Quality, Reliability, Manufacture, or Assembly etc. A good design is preferred to be performed by a designer in cooperation with a manufacturer. Products designed this way are generally well suited to ease manufacturing and the products will still fulfil the original requirements. The opposite is when the design team performs the design without any influence from any manufacturer, which can lead to a product that is difficult to produce. This is, according to Boothroyd *et al.* (2002), figurative called over-the-wall design as the designer only hands over the blueprint with no further communication. Fore the same reason, assembly workers must be included in the design process.

Generally, the information presented in the methods gives some form of guidelines of how to think in different situations, but also suggestions on the design processes. However, general information valid for all these methods will first be presented. The studied design methods can be of different kind; Guidelines, Qualitative methods and Quantitative methods. The studied methods include at least one of these.

Guidelines: Only design principles and guidelines are not fully sufficient when different designs should be compared or when a design should be refined. Guidelines, without ranking, cannot evaluate a design since they are just a set of rules, according to Boothroyd *et al.* (2002). However, guidelines are important as a base for a design method were they provide the designer with background information.

Qualitative methods: With a qualitative evaluation method, it is possible to rate different designs and compare them to each other. These methods compare different designs relatively to each other without measurable values.

Quantitative methods: If the time or cost saving for a redesign is desired, it is necessary to use a quantitative method. To calculate the time saving or the cost saving for a redesign, a database containing the time and cost for a certain operation is needed. This can also be called a knowledge-based approach.

3.2 Knowledge from the Precast Concrete Industry

In the precast concrete industry, elements and element connections have been developed during many years. Therefore it is important to consider this knowledge when development of a design method for connections in industrial constructions is carried out. In this section the most relevant guidelines will be presented, but it starts describing possible ways to connect precast concrete elements.

3.2.1 Connection Types

Today precast concrete elements are usually connected by bolts, grouting on site, reinforcement embedded in epoxy or by welding. Details that are connected by screws are often preferred prior to welded and grouted connections because they are faster and cleaner. Using screws and bolts is simple and safe, but on the other hand it demands more narrow tolerances. Reinforcement bars or screws can be fastened to elements in different ways; cast into an element, grouted into a drilled hole or glued to the elements. Grouting on site does not require small tolerances and the connections get strong. The quality is however weather depending, and it is not very time efficient. Gluing is not only dependent on weather, but the quality also depends on cleaning and drying. Welded connections are often easy to fit and adjust, but there can be a lack of quality level depending on the workmanship. Furthermore, welding is an unsafe fixation method with regard to i.e. worker safety, material damage and risk for fire. An example of assembly with prefabricated beams is shown in Figure 3.1. A threaded rod, which is normally cast into the support or fastened using a threaded insertion, is inserted through a hole in the beam. Often the threaded rod is fastened by nuts on the top of the beam and then grouted. If the hole is grouted the connection will be more ductile than without grouting. (Betongvaruindustrin, 2005)

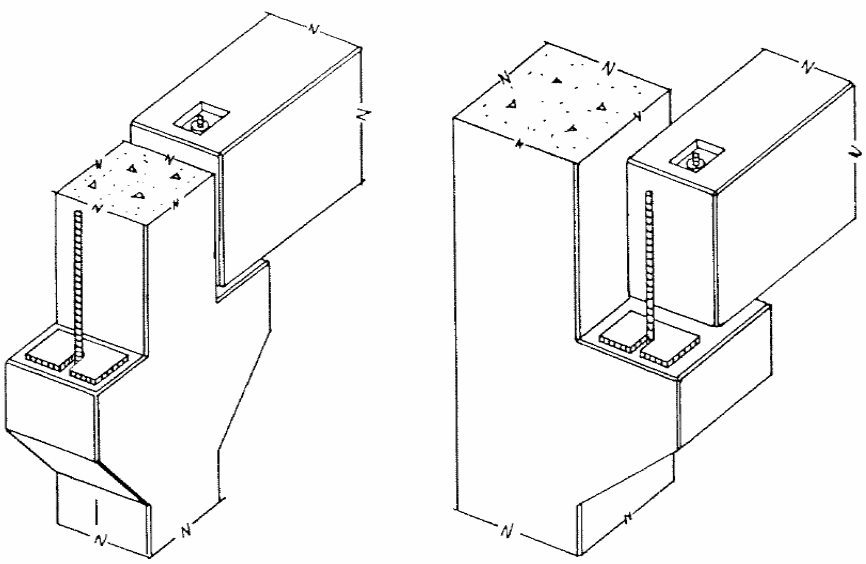


Figure 3.1 Examples of beams connected to columns, from Betongindustriens Landsforening (1996).

3.2.2 Guidelines for Precast Concrete

There are some guidelines regarding the erection of prefabricated concrete elements, according to *fib* (2007). These are shortly described below:

Accessible connections: Use connection types that are possible to access both during erection and afterwards.

Handling damage: Avoid parts that are fragile when handled. Parts that project from an element are in a vulnerable position. There is also a possibility to damage other elements with these parts.

Hook-up time: The time used for crane operation should be held to a minimum as it is expensive. Each element should be lifted into position and be put down so it is stable before it can be unhooked.

Load cases: There might be varying loads during the erection. All possible load cases have to be considered.

Plan the assembly: Make sure that all movements necessary for erection are possible to perform.

Reinforcement positions: All parts projected from an element should be designed so that they do not collide during erection.

Stability of the elements: Temporary supports should be prepared before the element is lifted into place.

Stability of the structure: The structure must be stable during the erection to avoid collapse.

Standardisation: Standardised connections should be used for similar situations as the need for skilled workers and the chance for errors decreases. Also the size of the components should be standardised to minimise the number of different parts.

Weather resistance: Avoid materials that are sensitive to varying weather, such as grout, epoxies and on-site cast concrete.

3.3 Design for Manufacture and Assembly ®

Boothroyd-Dewhurst Inc. has developed a design method called Design for Manufacture and Assembly (DFMA). It is a combination of DFM and DFA where DFM is aimed to ease the manufacturing process of the parts that will form a product and DFA is, as indicated above, a method to ease the assembly process. This could be achieved by reducing the number of parts needed for an assembly and the product should be as easy as possible to assemble with few possibilities for misassemble. This method is mainly developed for manufacturing and assembly of small products.

This section starts with a short description of the DFMA method and is followed by describing guidelines that are the base for the DFMA method, defining criteria for part reduction and assembly efficiency. Furthermore, time penalties for the evaluation method are described for several situations. In the end, some assembly methods are described. Unless otherwise is stated, the information in this section comes from Boothroyd *et al.* (2002).

3.3.1 Design Procedure

When designing according to DFMA the first part is DFA, which is important even if the assembly cost is low. This is because the DFA method, for example, reduces the number of parts which leads to a reduced manufacturing cost. A design for assembly also results in improved reliability and fewer defect parts. In Figure 3.2 the design procedure according to the DFMA method is presented. When the first DFA analysis is completed it might be necessary to carry out a DFM evaluation to make sure that the manufacturing process is not complicated by the changes due to assembly.

The method starts by minimising the number of parts in order to get an easier assembly. Thereafter the assembly time is calculated due to handling and insertion of parts. This is done using handling codes and insertion codes each giving time penalties which will be summed up to a total assembly time.

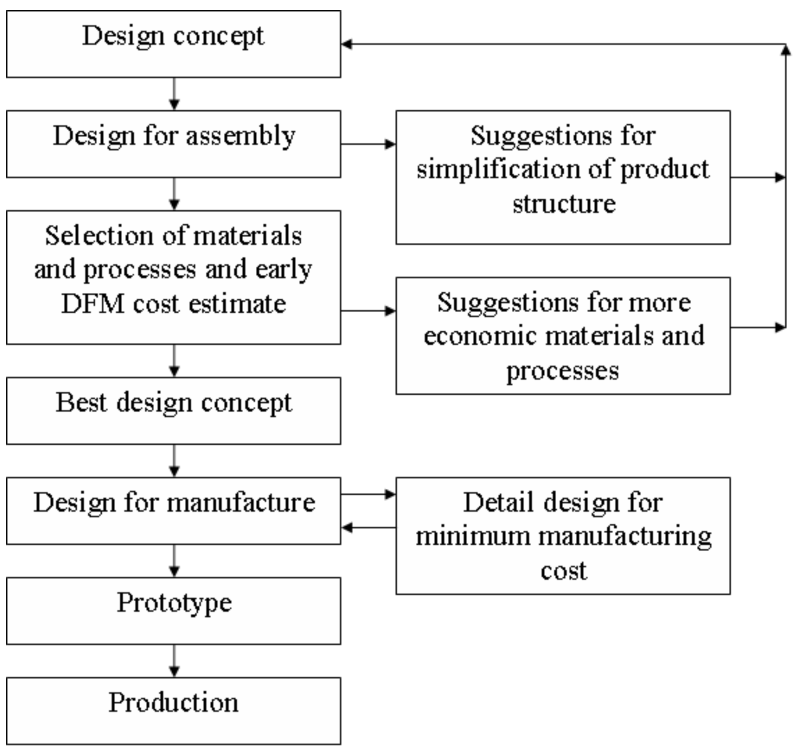


Figure 3.2 DFMA design procedure according to Boothroyd et al. (2002)

3.3.2 Assembly Guidelines

This section is divided into general guidelines, guidelines regarding handling and guidelines regarding insertion and fastening.

General Design Guidelines

Avoid over-constrained design: Use kinematic design principles to avoid an over-constrained design. Kinematics describes motions of bodies. Here, the interest is to fix parts without too many fixation points. This means that it can be possible to simplify the fixation of a part. A connection consisting of, for instance, three screws might be possible to simplify to just use one screw and one support. In this way, fewer screws or fasteners might be sufficient to keep the part stable and still transfer design actions.

Avoid restricted access: Make sure that there is enough space left for assembly operations. Place fasteners where they can be easily reached by the assembly worker.

Minimise the number of parts: The assembly cost is mainly influenced by the number of parts and their ease of handling, insertion and fastening. The number of parts in an assembly should always be kept to a minimum.

Use one material: If a stronger material is needed in some regions of a part, try to use the same stronger material in both regions even if it is more expensive. The savings in assembly will probably be greater than the cost for the more expensive material.

Guidelines Regarding Handling

Jamming and tangling: Prevent parts from jamming and tangling when stored and handled. If the parts tend to jam or tangle a lot of time might be needed to loosen the parts which also may require both hands of the assembly worker. Small changes in design may be sufficient to avoid jamming and tangling.

Others – small, sharp, slippery etc.: Avoid parts that stick together, fall apart or are slippery. Also avoid having too large or too small parts and parts that are fragile or sharp. All these properties can decrease the efficiency of assembly.

Standardise components: Avoid having one part for the right side and another part for the left side; try to use standardised parts within the assembly. A reduced number of different parts decrease the possibilities for misassemble and the cost for specific parts.

Symmetry: Parts are preferred to be as symmetrical as possible; they should preferably have end-to-end symmetry and rotational symmetry. Time can be saved if a part can be assembled in many orientations as the need for rotation and location is reduced. If a part needs to be asymmetrical for any reason, it can be slightly asymmetrical or pronounced asymmetrical. For manual assembly the parts should be made clearly asymmetrical. On the other hand, for robotic assembly it depends on if a visual system is available. With a visual system, a robot uses cameras to locate parts and to manoeuvre. A visual system might be expensive, but if it exists it can be sufficient to have just slightly asymmetrically parts. If there is no visual system, the asymmetry must, in some cases, be even more pronounced than for manual assembly. Boothroyd *et al.* (2002) states that a pronounced asymmetry is needed for robotic assembly due to the cost for a visual system, while Causey (1999) claims that only a small asymmetry is sufficient for robotic assembly.

Guidelines Regarding Insertion and Fastening

Assemble from above: The best way to assemble is, in general, around an axis from above, as the parts will stay due to gravity. If fastened from below it might be necessary to hold the part until fastened or inserted.

Avoid repositioning: Avoid turning over the incomplete assembly during the assembly.

Locate before release: Parts should be located before they are released. If a part must be released before it is located, there is a risk that the part will not be located correctly, e.g. when dropped in a hole.

Resistance to insertion: Provide generous tolerances for insertion in order to avoid friction and jamming during insertion. The mating parts should preferable be guided to the right location.

Secure parts: Loose parts should be secured as soon as possible after being located, otherwise time will be needed to hold down the parts in position. Self-locating parts are preferred.

Use simple fasteners: For manual assembly snap fits fasteners are preferred. Snap fits are the cheapest fasteners followed by plastic bending, riveting, and finally screw fasteners.

3.3.3 Criteria for Part Reduction and Assembly Efficiency

The DFA method starts reducing the number of parts, in order to ease the assembly, by answering the following questions:

- Does the part move relative all other parts?
- Must the part be of another material than other parts?
- Must the part be separated from the other parts, or else one or more of the other parts' assembly will be impossible?

A part that gives negative answers to all of these questions is superfluous. If the answer is positive to one or more of the criteria, the part considered is a critical part. The sum of all critical parts is called the theoretical minimum number of parts, n_{min}.

To be able to improve a specific assembly, it is important to know its assembly efficiency. The assembly efficiency, E_a, can be calculated by multiplying the theoretical minimum number of parts, n_{min}, to the basic assembly time for one part, t_{ba}, and then divide the sum by the estimated total assembly time, t_{ea}, see Equation 3.1. The basic assembly time is defined to be three seconds if there are no problems concerning handling, fastening or insertion, which is further discussed later.

$$E_a = \frac{n_{\min} \cdot t_{ba}}{t_{ea}} \qquad (3.1)$$

3.3.4 Assembly Evaluation

When an assembly process is to be classified, or when different designs are to be compared, it is necessary to consider several actions. First it is necessary to collect the parts to the place for assembly, so that all parts are within reach for the assembly worker. Sometimes several parts can be brought to the assembly station at the same time which leads to time savings. Then the parts have to be moved to their location in the assembly. This operation includes grasping of the parts and the actual movement of the parts. Further on, it might be needed to rotate the parts before they are in their right position. When inserting parts, there can be problems with e.g. jamming or friction which has to be considered. Next step is to fasten the parts. This operation demands various amount of assembly time depending on the kind of fastener and if the parts have to be held in position before fastening. If an assembly has to be turned over in order to perform the assembly work, extra time is needed. All operations described above demand some assembly time which has to be estimated. The time needed can be estimated by an analysis of the parts' properties, which is described below for some different properties. The times discussed are considered as penalty times given for different types of assembly problems. It might be possible to orientate a part while it is moved. Thus it might not always be correct to add the time penalties of different causes. Such a time penalty would be overestimated.

Symmetry Effects

The symmetry of a part can be defined with two angles; α and β. α-symmetry is the rotation angle that the part needs to be rotated around an axis perpendicular to the axis of insertion and β-symmetry is the rotation angle the part needs to be rotated around the axis of insertion, see Figure 3.3. Boothroyd *et al.* describe a total angle of symmetry which is the sum of α and β. The advantage of this approach is that only one single parameter is needed in order to get the time needed for rotation.

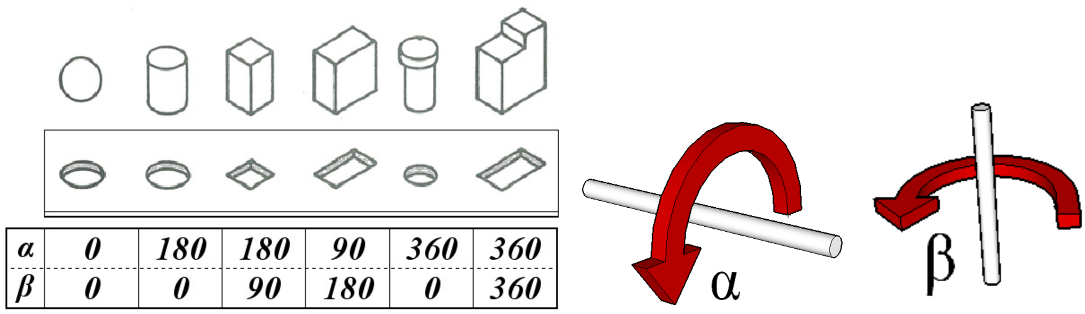


Figure 3.3 α and β symmetry, adopted from Boothroyd et al. (2002).

Size and Weight Effects

Handling time is influenced by the parts geometry. The thickness is defined as the maximum height of the thinnest direction from a flat surface. For cylinders (with diameter < length) the thickness is defined as the radius. A handling time penalty of up to 1.2 seconds will be the result of a thickness under 2 mm. Further on, the length is defined as the largest non-diagonal dimension of the part considered. A length less than 20 mm will result in a handling time penalty. These time penalties are due to the difficulty to grasp small parts. Parts that are so small that they need to be handled by tweezers should be avoided. The handling time penalty also applies for heavy parts which are calculated assuming manual assembly using one hand.

Additionally Effects

Both weight and size may cause the need for a two hand grip. Two hands might also be needed if the part is flexible, if the part needs to be handled carefully or if holding features are missing. Also tangling or nestling usually demands both hands.

Effects due to Chamfer Design

Chamfers are used to ease the insertion of a peg into a hole or the placement of a part with a hole onto a peg. There are formulas for calculation of the insertion time of a certain chamfer design. With chamfers both on the peg and the hole the insertion time will be approximately half the time as the insertion time would be without chamfers. It is more effective to have a chamfer on the peg than on the hole, and curved chamfers are more effective than conical but they are on the other side also more expensive.

Effects of Access, Vision and Special Fasteners

Time penalties up to seven seconds are given for screws assembled with restricted vision and clearance. Also the design of screws is considered. There is a time difference for screws fastened by hand or with help of a power-tool. The time penalties are derived from experiments. The penalty due to restricted access is up to one second while combined restrictions of access and vision result in a penalty of up to three seconds.

Effects of Holding Down

There is a basic time when inserting a peg through a hole in at least two materials that are prealigned and self locating. In addition to the basic time a time penalty is added if the materials need to be held down or to be aligned. The penalty time will vary depending on if the parts need to be held down and if they are easy to align or not. The time penalties vary significantly.

3.3.5 Application of the Methodology

Each assembly is given a handling code, consisting of two digits, which describes the difficulty of handling the part to be assembled. These handling codes can be seen in Table 3.1. The first digit concerns the symmetry (α and β) while the second takes into account the handling difficulties and thickness. An estimated average handling time, based on experiments, is given on the basis of the handling code; thus a time data base is needed. Times for insertion and fastening are calculated by formulas for different types of operations depending on for instance chamfer design and clearance. These formulas are not considered further in this project. Times for acquisition, i.e. times needed to collect material and equipment, also have to taken into account.

A total assembly time, t_{ta}, can be calculated from the average times, see Equation 3.2. Here the acquisition time, t_{acq}, is added to the number of parts, n, times the sum of the handling time, t_h, and the insertion time, t_i.

$$t_{ta} = t_{acq} + n \cdot (t_h + t_i) \tag{3.2}$$

The average times discussed previously can be changed a lot for different types of assemblies. For example, the time to manually fasten a screw is 8.2 seconds on average but if the screw is auto fed the fastening time can be reduced to 2 seconds. For a large assembly a screw can require even longer time to be fastened.

The possibility to eliminate parts can be evaluated using the three conditions discussed earlier in Section 3.3.3. Further on, the DFA index can be calculated and the cost can be estimated by adding the total part cost to the cost of the assembly workers per hour times the total assembly time. A table of possible eliminations or design changes can be created. The table can also show the time saving of each design change.

Table 3.1 Examples of handling codes according to Boothroyd et al. (2002).

Handling codes, shown in the grey fields, depend on symmetry and size		No handling difficulties			Part nests or tangles		
		Thickness > 2mm		< 2mm	Thickness > 2mm		< 2mm
		Size > 15mm	6mm > Size > 15mm	Size < 6mm	Size > 15mm	6mm > Size > 15mm	Size < 6mm
		0	1	2	3	4	5
α+β < 360	0	1.13	1.43	1.69	1.84	2.17	2.45
360 < α+β < 540	1	1.5	1.8	2.06	2.25	2.57	3.0
540 < α+β < 720	2	1.8	2.1	2.36	2.57	2.9	3.18
α+β = 720	3	1.95	2.25	2.51	2.73	3.06	3.34

3.3.6 Manual Assembly Methods

The times needed for part acquisition presented in the DFMA method are for small parts and when all parts are within an arm length from the assembly worker. No major body motions are assumed to be required. If the parts are further away from the worker or heavy or large, other time figures are needed. There are different kinds of assemblies, namely Bench assembly, Multistation assembly and Modular assembly centre, which can handle part sizes up to about 85 centimetres. Custom assembly layout and Flexible assembly layout suit parts that are larger. All these assembly methods concern assembly on a special assembly place, which is not always possible. For instance when installing an elevator, the assembly has to be performed on site. This will result in an increased handling time when tools, material and parts need to be transported. The time for acquisition differs depending on the location of the parts, the distance from a part to its assembly, the part weight and if one or several parts are collected on the same time. Boothroyd *et al.* have divided parts into three weight categories starting with normal parts able to be handled by one person. If the part is heavier, two persons are needed for the handling, and for even heavier parts lifting equipment is needed.

3.3.7 Design for Manufacture

When a DFA analysis is completed a DFM analysis follows. For the manufacture of a specific part many combinations of processes and materials can be chosen. For instance, one material can be sand cast while another material can be processed by injection moulding. The processes and materials available can be more or less easy, or even impossible, to combine. Membership functions can be used to see if a chosen combination is possible. A membership function gives a value between zero and one where zero means impossible to manufacture and one means easy to manufacture. The values are depending on the material, size, shape etc. There are some computer programs that guide the designer through the choices of manufacturing. Programs can be built up using conditions as; if condition A and B are fulfilled than action C will be initiated. Also the strength and modulus of elasticity of the available materials have to be considered. Further on, it is important to get a cost estimation of the manufacture. An estimated cost can be calculated with computer programs. The cost depends on shape, material, processes and quantity.

3.4 Design for Assembly According to Bralla

There is a design-for-manufacture handbook written by Bralla (1999) which also handles design for assembly (DFA). Bralla's method consists of guidelines that are similar to the guidelines in the DFMA method developed by Boothroyd *et al.*, described in the previous section. The method starts with minimising the number of parts, also inspired by Boothroyd *et al.*, and continues with simplifications of the remaining parts using guidelines. Most of the guidelines are the same as in the DFMA method but some are different or more detailed, these are described below:

Add parts: In some cases, an improvement can be achieved by adding an extra part as this might allow more liberal tolerances. It is though important to avoid adding too many parts to a design.

Design over-sized holes: When inserting, for example, a peg into a hole, it is beneficial if the hole is of over-size. This is for the same reason as the previous point, self-guiding, but also due to the risk of jamming.

Gather all electronics: Try to locate all electronic components in the same place of a product. In this way no extra wires are needed between different components. With all components in the same location the rest of the part might be easier to design.

Minimise the amount of fasteners: It is better to have few large fasteners than many small. In this way the time for assembly will be decreased, but also the time spent on handling loose parts.

Use integrated hinges: For some materials, especially plastics, hinges can be made within a part. Integral hinges can be achieved if a thinner section is formed at the location for the hinge. In this way, material can be saved.

Use integrated springs: In many cases, springs can be difficult to mount. Therefore, when it is possible, parts should be designed to act in a flexible way to avoid the need for extra springs.

Use self-aligning parts: In order to minimise the assembly time, self-aligning parts should be used. With self-guiding parts, the assembly position do not need to be exact in order to mount the part.

3.5 Lucas Design for Assembly Evaluation Method

This knowledge-based method, called the Lucas DFA evaluation method, is built up around an assembly sequence flowchart and it has grades derived from studies. The method is best suited for production of small products. This section is based upon a study on the DFA evaluation method, made by Redford and Chal (1994). The method is systematic; important aspects of assemblability and component manufacture are considered and rated. The design evaluation follows the procedures shown in Figure 3.4, here including design for manufacture. The evaluation starts with a product analysis where it is important to decide if the design is unique. If a similar design exists, there might be an opportunity for standardisation. Usually, other DFA systems only consider the current assembly and do not use the knowledge from previous designs.

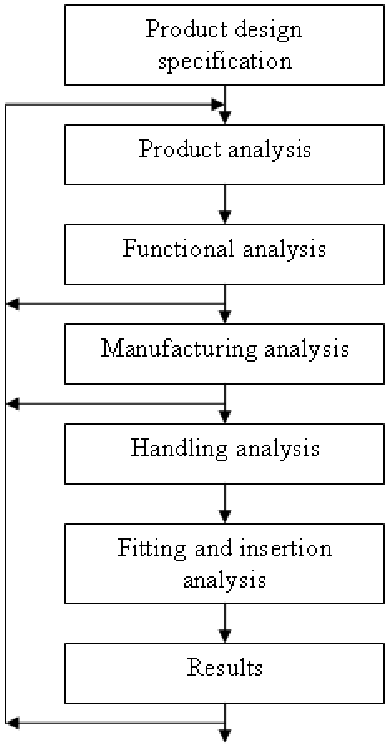


Figure 3.4 The Lucas DFA procedure, according to Redford and Chal (1994).

The next step in the procedure is a functional analysis of the assembly. Different activities are categorized by their functionality. Each part in the assembly is analyzed and assigned to be either essential (Category A) or non-essential (Category B). The design efficiency, E_d, is then defined as the ratio; number of essential parts, n_A, divided by the total number of parts, n, see Equation 3.3. Assembly cost can then be reduced by eliminating or combining parts that are non-essential.

$$E_d = \frac{n_A}{n} \tag{3.3}$$

To eliminate complex designs containing few complex parts an additional design for manufacture (DFM) analysis is carried out as the next step in the procedure. This is necessary as few complex parts might result in a greater cost for manufacture than the gain in easier assembly.

The DFM analysis is followed by an analysis of the handling (or feeding). The analysis includes questions about for example tangling, nesting, fragility, etc. resulting in a handling index, I_h, for each part. In Table 3.2 the index is presented depending on each of the following subjects; the parts' size, weight, orientation, handling difficulties and rotational orientation. If the index is under 1.5 the part is satisfying else improvement suggestions are given. A total handling ratio, R_h, for the whole assembly is determined as the sum of all handling indexes divided by the total number of essential parts, n_A, as shown below in Equation 3.4.

Table 3.2 Handling index for the Lucas DFA method, adopted from Chan and Salustri (2005).

Handling Index: $I_h = A + B + C + D$			
A	**Size and weight of parts** (One of the following)	Very small – requires tools	1.5
		Convenient – hands only	1.0
		Large and/or heavy – requires more than one hand	1.5
		Large and/or heavy – require hoist or two people	3.0
B	**Handling difficulties** (All that apply)	Delicate	0.4
		Flexible	0.6
		Sticky	0.5
		Tanglible	0.8
		Severely nest	0.7
		Sharp/Abrasive	0.3
		Untouchable	0.5
		Gripping problem / slippery	0.2
		No handling difficulties	0.0
C	**Orientation of part** (One of the following)	Symmetrical – no orientation required	0.0
		End to end – easy to see	0.1
		End to end – not visible	0.5
D	**Rotational orientation of part** (One of the following)	Rotational symmetry	0.0
		Rotational orientation – easy to see	0.2
		Rotational orientation – hard to see	0.4

$$R_h = \frac{\sum I_h}{n_A} \qquad (3.4)$$

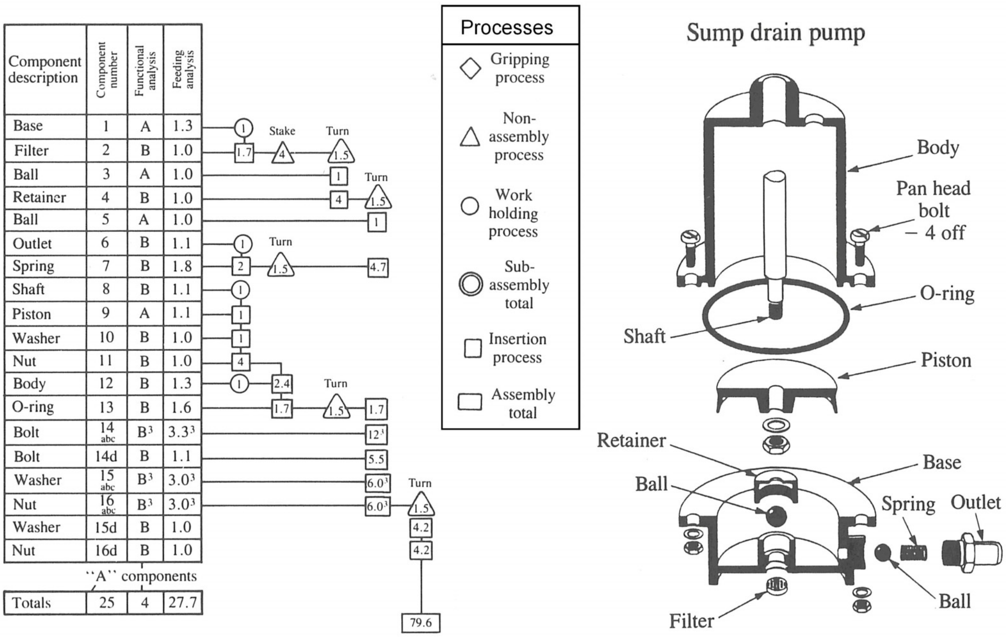
The method continues with a fitting and insertion analysis using sequence flow-charts. To be able to identify processes that are expensive, each individual process is assigned a fitting index, I_f. The part fitting index, which is presented in Table 3.3, has a maximum recommended value of 2.5 and gives an indication of how these processes might be changed. The insertion analysis includes holding, gripping, insertion and other actions e.g. movements and transports. Finally a fitting ratio, R_f, is calculated, see Equation 3.5, as the sum of all fitting indexes divided by the total number of essential parts.

Table 3.3 Fitting index for the Lucas DFA method, adopted from Chan and Salustri (2005).

Fitting Index: $I_f = A + B + C + D + E + F$			
A	**Part placing and fastening** (One of the following)	Self-holding orientation	1.0
		Requires holding	2.0
		Plus one of the following	
		Self-securing (i.e. naps)	1.3
		Screwing	4.0
		Riveting	4.0
		Bending	4.0
B	**Process direction** (One of the following)	Straight line from above	0.0
		Straight line not from above	0.1
		Not a straight line	1.6
C	**Insertion** (One of the following)	Single	0.0
		Multiple insertions	0.7
		Simultaneous multiple insertions	1.2
D	**Access and/or vision** (One of the following)	Direct	0.0
		Restricted	1.5
E	**Alignment** (One of the following)	Easy to align	0.0
		Difficult to align	0.7
F	**Insertion force** (One of the following)	No resistance to insertion	0.0
		Resistance to insertion	0.6

$$R_f = \frac{\sum I_f}{n_A} \tag{3.5}$$

To get more understanding an example of a drain pump, according to Redford and Chal (1994), is shown in Figure 3.5 and Figure 3.6 below. In the example, an original design is compared to an improved design.



Component description	Component number	Functional analysis	Feeding analysis
Base	1	A	1.3
Filter	2	B	1.0
Ball	3	A	1.0
Retainer	4	B	1.0
Ball	5	A	1.0
Outlet	6	B	1.1
Spring	7	B	1.8
Shaft	8	B	1.1
Piston	9	A	1.1
Washer	10	B	1.0
Nut	11	B	1.0
Body	12	B	1.3
O-ring	13	B	1.6
Bolt	14 abc	B³	3.3³
Bolt	14d	B	1.1
Washer	15 abc	B³	3.0³
Nut	16 abc	B³	3.0³
Washer	15d	B	1.0
Nut	16d	B	1.0
Totals	25	4	27.7

Design Efficiency:

$$E_d = \frac{n_A}{n} = \frac{4}{25} = 16\%$$

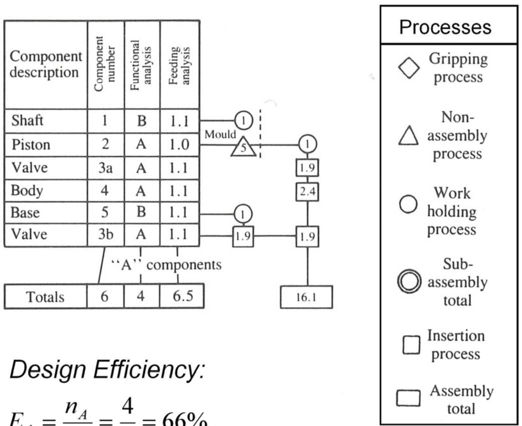
Total Handling Ratio:

$$R_h = \frac{\sum I_h}{n_A} = \frac{27,7}{4} = 6,9$$

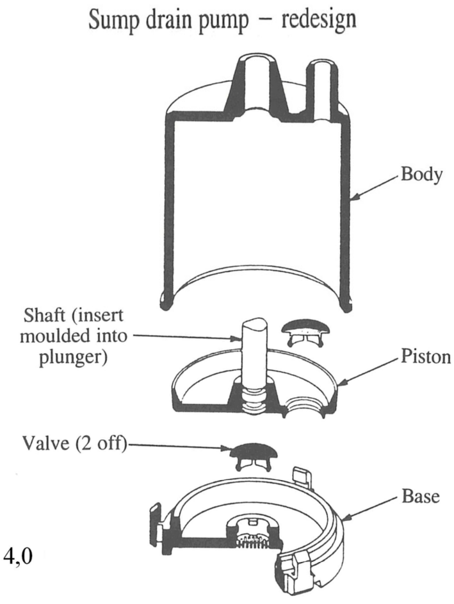
Fitting Ratio:

$$R_f = \frac{\sum I_f}{n_A} = \frac{79,6}{4} = 19,9$$

Figure 3.5 Sequence assembly flow-chart for a drain pump, original design, adopted from Redford and Chal (1994)



Component description	Component number	Functional analysis	Feeding analysis
Shaft	1	B	1.1
Piston	2	A	1.0
Valve	3a	A	1.1
Body	4	A	1.1
Base	5	B	1.1
Valve	3b	A	1.1
Totals	6	4	6.5



Design Efficiency:

$$E_d = \frac{n_A}{n} = \frac{4}{6} = 66\%$$

Total Handling Ratio:

$$R_h = \frac{\sum I_h}{n_A} = \frac{6,5}{4} = 1,63$$

Fitting Ratio:

$$R_f = \frac{\sum I_f}{n_A} = \frac{16,1}{4} = 4,0$$

Figure 3.6 Sequence assembly flow-chart for the drain pump after improved design, adopted from Redford and Chal (1994).

3.6 The Hitachi Assemblability Evaluation Method

In the late 70-ties, the Hitachi Assemblability Evaluation Method (AEM) was developed by *Hitachi Ltd* and it is described by Redford and Chal (1994). The main objective of the method is to improve design quality by identifying weaknesses in the design at an early stage of the design process. According to the Hitachi method it is important to consider both the cost and the quality of an assembly due to the fact that simple and cheap parts do not always give the least expensive design. Therefore the method measures both the cost and quality by two ratios:

1. An assemblability evaluation score ratio, *E*, used to estimate the design quality by determining the difficulty of operations

2. An assembly cost ratio, *K*, used to estimate assembly costs

The Hitachi AEM is based on a procedure starting with categorizing possible assembly operations into approximate 20 elemental assembly tasks. Each task is given a symbol clearly indicating the content of the task. These tasks relate to insertion and fastening but not to part handling. Each elemental task is then given a penalty score, P_s, which reflects the degree of difficulty of the task. Different factors that might influence the elemental tasks are treated as coefficients modifying the penalty score. The definition of the assemblability evaluation score, E_{part}, of the task is the sum of all penalty scores subtracted from the highest possible score, 100 points, see Equation 3.6. Finally the total assemblability evaluation score for the product, E_{tot}, is defined as the sum of all assemblability scores of the individual tasks, divided by the number of parts, *n*, see Equation 3.7. If the value is under 80, improvements should be made. The total score does not provide all the information concerning reduction of the number of parts; it is still possible to improve the score by increasing the number of parts with higher-than-average assemblability evaluation score. To avoid this, a cost ratio, *K*, is used, see Equation 3.8. The ratio is defined as the assembly cost of the redesigned product, C_{re}, divided by the assembly cost of the original product, C_{orig}. If the ratio is higher then 0.7 improvements are made. The results of the method are confirmed by continuously comparing estimated assembly cost ratio with the actual ratio. If the difference is small it is acceptable otherwise an examination is carried out to determine possible errors. An evaluation example of a connection is shown in Figure 3.7.

$$E_{part} = 100 - \sum P_s \qquad (3.6)$$

$$E_{tot} = \frac{\sum E_{part}}{n} \qquad (3.7)$$

$$K = \frac{C_{re}}{C_{orig}} \qquad (3.8)$$

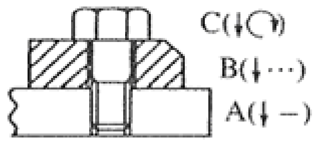
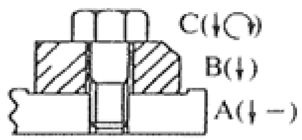
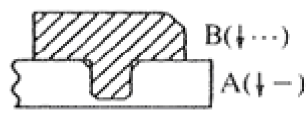
Product structure and assembly operations			E_{part}: Part assemblability evaluation score	E: Assemblability evaluation score	K: Assembly cost ratio	Part to be improved
First design		Set chassis A	100	73	1	B
		Bring down block B and hold it to maintain its orientation	50			
		Fasten screw C	65			
1:st redesign		Set chassis A	100	88	app. 0.8	C
		Bring down block B (orientation is maintained by spot-facing)	100			
		Fasten screw C	65			
2:nd redesign		Set chassis A	100	89	app. 0.5	B
		Bring down and pressfit block B	80			

Figure 3.7 Example of evaluation according to the Hitachi assemblability evaluation method, adopted from Redford and Chal (1994).

3.7 Design for Assembly On-Site

Lassl and Löfgren (2006) have developed the method design for assembly on-site, DFA(OS), which consists of guidelines concerning assembly at construction sites. Some of the conclusions will be presented in this section.

As discussed in the previous chapters the assembly should be quick, easy and clean. It is also important that the elements are assembled in their final position from the start, with small help from large tools and robotics. Further on, Lassl and Löfgren discusses that connections should be made in such way that they only need to be locked from the inside of the building, which eliminates the need to work on the outside on the façade, which could be difficult. Further discussed are the needs for movement of special tools during construction. It is the opposite of the manufacturing industry where special tools can be fixed at one location. The method includes guidelines presented below.

Assembly order and stability: Elements are preferred to be assembled from the top down. If an element should be possible to disassemble in the future without demounting the whole building, it should be mounted from the side. This is due to the fact that it is impossible to lift an element with another one on top of it. To avoid temporary supports an element can be designed with moment resisting connections which makes it stable without further support.

Flexibility: It is important that the connection is flexible and able to use in different ways. It should be possible to mount and lock the connection from different directions. It is still essential that the connection does not get too complicated.

Handling and ergonomics: Elements are often moved by cranes, which have limited precision. Therefore self-location elements are preferred. Connection details can also be used as lifting points for the elements with the demand that the elements are able to hang straight. The assembly workers' ergonomics is another important aspect, over-head work and use of ladders should be avoided.

3.8 Design for Assembly 2

IVF, the Swedish engineering industry's research institute, has developed an assembly method called Design for assembly 2, DFA2, and it is presented by Rapp and von Axelson (2003). The evaluation method gives both a qualitative and a quantitative judgment of industrial assembly processes. The qualitative judgment is based on assemblability and gives a grade, while the quantitative judgment is based on the time needed for assembly operations given in seconds. The method is developed for automatic assembly and it is based on the conditions that only one detail is handled at the same time, all details are ready for assembly at the assembly position and they can be handled by one person. The evaluation process is performed by simple rules which result in nine points for a good design, three points for an acceptable design and one point for an unwanted design. An assembly index is defined as the actual grade divided by the maximum possible grade.

The method contains two levels; a product level and a detail level, further described below. Questions concerning the total product are handled in the product level and detail related questions are treated in the detail level. Some of the subjects are already handled in the DFMA method in Section 3.3.

Examples of the evaluation scores and DFA times are shown in Table 3.4 and Table 3.5. It can be seen that the highest grade corresponds to the lowest assembly time. The result from the DFA2 analysis is an average detail score, i.e. a score for a whole product, as well as the score for a certain detail. Also an assembly index is calculated as the actual score divided by the maximum possible score. Finally, the number of parts and the minimum number of parts are shown.

Table 3.4 Grades concerning tolerance chains, from Rapp and von Axelson (2003).

Tolerance chains	Product
A tolerance chain is the sum of tolerances influencing the assembly process. Tolerance chains should be minimised in order to get a safer assemble process, not using subassemblies.	Point
No tolerance chains in assembly, only the tolerances of the parts themselves.	9 p
Tolerance chains for two parts exist in the assembly.	3 p
Tolerance chains for three or more parts exist in the assembly.	1 p

Table 3.5 Grades and assembly times concerning assembly movements, from Rapp and von Axelson (2003).

Assembly movements	Connections between details	
The fixation movement of a detail is faster for a simple motion	Point	DFA time
The assembly movement consists of a compression movement of one detail to be assembled.	9 p	0 s
The assembly movement consists of another movement than compression of one detail to be assembled.	3 p	0.5 s
The assembly movement consists of another movement than compression of several details at the same time.	1 p	0.8 s

3.8.1 Product Level

The subjects of the questions for the product level are presented shortly below:

Assembly directions: A product is preferred to only be assembled from one direction.

Base objects: An assembly should preferably start from a base object on which all other parts are assembled.

Designing base objects: The base object should be easy to handle and transport.

Parallel operations: Designers should aim for parallel operations.

Reduce the number of details: Keep the total number of details low, as well as the number of unique details.

Tolerance chains: Avoid tolerances depending on more than one part.

Unique details: Standard details are better to use than unique special details.

3.8.2 Detail Level

Below the subjects concerning detail level are described shortly:

Accessibility: Good access and space for assembly tools are required.

Adjustment: Avoid the need for adjustments in assembly and make the design fool proof.

Fastenings: The number of connections in a product should be minimised. Use simple movements. A special tool might be able to reduce the number of details.

Form: The form can be used for orientation, hinder rotation, be symmetrical or pronounced asymmetrical. Symmetry is measured in the same way as in the DFMA method described in Section 3.3.

Fragile details: Avoid fragile details as handling can harm parts.

Gravity centre: The gravity centre of a part should either provide stability or be pronounced eccentric.

Gripping: Design parts that are easy to grip, and try to make different details possible to grip in the same way.

Holding down: Fix details as soon as they are located.

Insertion: Avoid the need for exact positioning. Use large tolerances for insertion and use chamfers.

Integration: Try to combine parts using the criteria in Section 3.3.3 developed by Boothroyd *et al.* (2002).

Length: Long details should be avoided.

Movements in assembly: Use simple movements in assembly operations. Pressure is easiest followed by pulling and movement sideways. Rotation is the most time consuming assembly motion.

Orientation: It is advantageous if the orientation from manufacture of parts can be used in the assembly process, this way no reorientation will be needed.

Tangling: Parts should preferably be prevented from tangling.

Tolerances: Do not use smaller tolerances than necessary.

Turn around: Avoid operations that require turning the assembly over.

Weight: The weight of details should be kept to a minimum.

4 Analysis of Design Methods

In this chapter the design methods presented in Chapter 3 will be analysed and compared. Needs for improvement are discussed as well as the possibilities to adopt ideas from the methods into connection design in industrial construction. However, the chapter starts with discussing differences between building industry and manufacturing industry.

4.1 Building Industry *vs* Manufacturing Industry

In order to analyse the design methods it is important to point out the differences between manufacturing industry and building industry. Here, some of the differences are discussed.

For application in building industry the studied design methods must be adjusted due to size effects. The whole assembly will be larger when constructing a building. The assembly, and also the parts, is often much larger than the assembly workers. Further on, heavy parts are used in building industry, which demands lifting assistance such as cranes. The time needed for lifting and transportation has to be considered in another way for industrial construction as the handling time increases compared to manufacturing industry. Extra crane time is needed for elements that have to be moved a long distance. In some cases connections can be used as fixation points for lifting devices when elements should be lifted, see Section 3.7, which will affect both the elements and their connections. This is not considered in any of the design methods for manufacturing industry.

In manufacturing industry the final assembly is usually performed in a suited location. This is not the case in traditional building industry where the assembly is made at a new building site for each new project. Moreover, a product produced in manufacturing industry is often made in thousands copies. A building however is usually built in one or few copies. It is unusual to produce the same house in many copies or in many areas. A building system, on the other hand, can be used over and over again. Prototypes are often produced during development of a product in manufacturing industry. In building industry the prototype is commonly also the final product, especially if only one house of the same type is to be built. Connections in a building system can, on the other hand, be developed using prototypes of smaller parts or details. It is though important to stress the difference between connections used in a system with volume elements and a system with linear elements etc.

During traditional building design, it is common to perform the architectural work before the construction design. This leads to a late introduction of design methods, if such are used. However, the design work in manufacturing industry often starts using these methods. If the methods are used in building industry, design for assembly seems to be more important than design for manufacture. An assembly at a construction site is both time and cost consuming. The manufacturing of parts and details might be more important in manufacturing industry.

Symmetry can be hard to use in buildings as a wall cannot be made symmetrical upside-down or inside-out. Further on, a floor element is hard to design so that it can be assembled upside-down. On the other hand, symmetry can be used in smaller details such as bolts, dowels and other connection details which are commonly used in manufacturing industry.

4.2 Analysis and Needs for Improvement

In this section all methods presented in Chapter 3 will be analysed. Parts of the methods that are useful for the building industry will be identified for further use. Also weaknesses of the methods are discussed. All methods will be commented separately below. Finally, possible starting points of the design work are discussed. But first all methods are compared and their characteristics are presented

4.2.1 Content of the Studied Methods

When evaluating design proposals there are two main types as described in Section 3.1; qualitative evaluation, which consider the ease for assembly relatively, and quantitative evaluation, which gives an estimated assembly time or cost. A method that gives the savings in time or cost for a certain improvement can be more favourable than a method that only ranks possible improvements. However, a quantitative method demands some sort of database with times or costs for all possible operations. There are also methods consisting of only guidelines. The methods studied are of all variants, as shown in Table 4.1.

Table 4.1 Compilation of the design methods described in Chapter 3.

Design Method	Guidelines	Qualitative Grade	Quantitative Time or Cost
Precast Concrete Industry	X	–	–
Boothroyd et al DFMA	X	–	X
Bralla DFA	X	–	–
Lucas DFA	–	X	–
Hitachi (AEM)	–	X	X
DFA(OS)	X	–	–
DFA2	X	X	X

4.2.2 Knowledge from the Precast Concrete Industry

The precast concrete industry has many relevant guidelines possible to use in connection design, for instance the ones concerning hook-up time, stability of elements, standardisation, handling damages and accessibility, see Section 3.2.2. However, it is important to note that the precast concrete industry is not a fully industrial construction method according to the definition of industrial construction used in this project, see Section 1.1. For example there exist guidelines for temporary supports, while the aim is to have a construction without them. Furthermore, methods like welding and grouting, which are possible to use in the precast concrete industry, should be excluded from the industrial construction process. This leads to harder demands on e.g. tolerances. A screw connection, or a snap fit connection, usually has a more narrow tolerance then a welded or grouted connection. A house built of precast concrete elements usually demands more supplementary work than a house build by totally industrialised elements. Another important aspect is the lack of a developed methodology, only guidelines are presented.

4.2.3 Design for Manufacture and Assembly®

The DFMA method developed by Boothroyd *et al.*, see Section 3.3, results in an estimation of assembly time depending on assembly difficulties; e.g. if the pieces to be assembled are small and tweezers have to be used. The methodology with handling codes might be possible to use in evaluation of structural connections, but then it has to be decided which parameters that these codes should be based on and how they should be graded. If an assumption of the time consumption or cost for an assembly is wanted, the codes have to be related to a database or time bank containing assembly times or costs for all possible assembly steps. The time needed to fasten a screw or a nut using different tools may vary a lot. Further on the time needed to put an element into position differs greatly depending on the connection type and size of element used. If the cost is to be estimated, many parameters have to be collected. Moreover, the cost is highly depended on the time used for assembly.

A data base with assembly times will be hard to accomplish since it has to be based on experiments or real building projects. Accordingly, a hard work has to be performed in order to create such a method. Nevertheless, it would be useful as the result is quantitative.

When a method should be developed for connection design, the size demands presented must be changed. A wall element, for example, is much larger than 2 or 20 mm. Instead it might be hard to handle parts smaller than, for instance, 20 mm if the assembly workers wear gloves. For large assemblies also the time for transports on the assembly site has to be considered. Transport distances might be longer and parts might be larger and heavier which influences the handling time. The database of assembly times is developed for small assemblies and will not give a correct approximation for an assembly of large parts.

Useful guidelines from the DFMA method are for example those handling the number of parts, access, simple fasteners and handling problems such as jamming and tangling. It is also important to locate parts before they are released which is discussed in the DFMA method. It is, on the other hand, irrelevant to use a guideline that recommends that the assembly should not be turned over, as this will never be a problem in a building process. Parts that are small, sharp and slippery are not very common in building industry, but it is however wise to avoid such details.

The method using criteria for part reduction is an effective tool for simplification of products. These criteria could be as useful in building industry as they are in manufacture industry.

4.2.4 Design for Assembly According to Bralla

The design for assembly method developed by Bralla, described in Section 3.4, has several guidelines similar to the design for manufacture and assembly method. There are no evaluation procedure in this method; only guidelines. Bralla discusses that it may be beneficial to add extra parts in order to ease the assembly. This can be difficult to combine with the criterion concerning part reduction, but it is however important to consider if adding an extra part may result in an easier assembly. Another guideline that can be of interest to use in building industry is to use fewer and larger fasteners rather than many smaller ones.

4.2.5 Lucas Design for Assembly Evaluation Method

This method, which is described in Section 3.5, considers the design efficiency in addition to handling and fitting of parts, which are handled separately. Both the handling and fitting ratios are simple to use and to compare between different design proposals. Also the design efficiency could be interesting in building industry. A method structured in this way should probably also suit structural connection design. The criteria must however be edited since they are developed to fit design in manufacturing industry; some criteria can be added and some can be removed or changed.

4.2.6 Hitachi Assemblability Evaluation Method

The Hitachi method is build up based on twenty elemental assembly tasks. If the method should be adjusted for connection design, these tasks have to be adjusted. A method structured this way is limited to the predefined assembly tasks which restrict the design proposals to connections only consisting of traditional assembly operations. New assembly types cannot be judged by such a method.

4.2.7 Design for Assembly (On-site)

The DFA(OS) method, developed by Lassl and Löfgren, consists mainly of guidelines. These guidelines are, on the other hand, well adapted to building industry. It is however important to develop an evaluation system so the guidelines can be used in an evaluation process.

Part reduction is also handled by this method. DFA(OS) uses the same part reduction method as both the design for manufacture and assembly method by Boothroyd and the design for assembly method by Bralla. This part reduction method is applicable in its present form also for building industry.

4.2.8 Design for Assembly 2

The structure of the method is good and easy to follow with the three levels of each criterion. It is however necessary to adjust the criteria to fit connection design in building industry. With the right type of questions the evaluation will show a good result regarding the qualitative evaluation. The quantitative part of the method, the assumed assembly time, has to be adjusted before it can be used in building industry.

4.3 Starting Point for Design

Before starting the design of a connection it is essential to decide which starting point to use for the design. Generally there exist two starting points, further described in the following text. Iteration is needed between these two extremes. In this way all demands are considered and a compromise is often the result. The two extremes are as follows:

Start with the connection: One approach is to start with the connection design. The idea is to make the connections as good as possible first and then continue with the design of the building system. In this case the connections will set the limitations of the elements and their design. It will for example decide how many connection points the element needs in order to resist the design load.

Start with the system: The other approach is to start with the building system design. When the system is decided the connections are designed to fit the demands. For example it can be decided that the element should have two connection points and that these connections must withstand the design load.

5 Connection Design Method

In the previous chapter the studied methods from Chapter 3 were analysed and possibilities to use them in connection design were discussed. Also the needs for improvement, in order to fit the building industry, were identified. With the knowledge from the analysed methods as a starting point, a method for connection design in industrial construction was developed which is presented in this chapter. But first, demands on a design method, considered during the development of the method, will be discussed.

5.1 Demands on Design Methods

A design method has to fulfil several demands. Below, desired properties for design methods are described followed by a presentation of functionality requirements for design methods.

5.1.1 Design Method Properties

Redford and Chal (1994) describes four properties relevant for a design method. These properties have been used as a starting-point during development of the new design method. A design method should be:

Complete: Many methods mostly have objective parts, while suggestions of how to improve an insufficient design are not given. However, design methods should be both objective and creative; they should both evaluate design proposals and give suggestions for improvements. Assembly problem areas should be brought to the users' attention and the method should give the designer the opportunity to freely decide how to improve the design.

Systematic: It is important that all relevant information concerning a design proposal is handled in design methods. Therefore, step-by-step procedures that are systematic are preferred to be used.

Measurable: The method should give results that are of interest to designers. One central problem is to measure for instance assemblability in an objective way. It may be difficult to see how much a certain design costs as there are many design solutions possible, each one resulting in a specific time and cost. It is also important that it should be easy to compare different design alternatives.

User-friendly: Designers often have little time to learn new methods; they must therefore be easy to use. Furthermore, it must at the same time give reliable results. These two demands are contradictory to each other; the method might not be used if it is too complex and if it is too easy the quality and the accuracy of the result might be too low. It is also important that the method gives quick results.

5.1.2 Functionality Requirements

Huang (1996) describes ten functionality requirements set on design methods. The requirements are divided into two parts; the first part concerns basic functions which should be fulfilled and the second part concerns more advanced functions which are preferred to be fulfilled. The requirements according to Huang are as follows:

Basic Functions

- Gather and present facts.
- Measure performance.
- Evaluate if a product design is good enough.
- Compare design alternatives: Which design is better?
- Highlight strengths and weaknesses.

Advanced Functions

- Diagnose why an area is strong or weak.
- Point out how a design can be improved.
- Predict "what-if" effects.
- Carry out improvements.
- Allow iteration to take place.

5.2 A Four Step Method for Connection Design

As a result of the analysis, see Chapter 4, a four-step design method has been developed, compiled in Appendix A. The design procedure is illustrated in Figure 5.1. Each step will be further described is separate sections, but they will be introduced shortly in the following text. The design method starts with guidelines that are presented in order to provide the designer with background information of connection design in industrial construction. This background information is aimed to help the designer to develop industrial connections that are easy to assemble. Before continuing with the method, a description of the design proposal has to be added by the user. In the description, assumptions should be described in order to make it possible to later understand the choices made by the designer. The next step is absolute demands; if a connection should be evaluated it is important to first make sure that the connection fulfils its absolute demands. These demands have to be fulfilled in order to make the connection work properly, e.g. the load bearing capacity has to be fulfilled. The absolute demands are checked with help of a checklist. If the absolute demands are fulfilled the next step in the method is to evaluate how well the connection is suited for assembly. The evaluation concerns desirable demands; if these demands are neglected the assembly might be more difficult but the connection will still function correctly after assembly. The evaluation consists of criteria related to assembly which are divided into statements. The connection performance is graded depending on the chosen statement of each criterion. The result of the evaluation is an assembly index, which describes the connection's assemblability relatively, and a list of which areas that can be improved. The improvement can either be a change of the connection itself or a change of the whole system. After the changes it is important to verify that the absolute demands still are fulfilled; the method should be used iteratively in the design process. When a connection has satisfactory result in the evaluation the next step can be performed; reduce the number of parts of the connection by eliminating unnecessary parts. The main reason for the part reduction is to make the assembly easer as fewer parts will result in an easier assembly. Besides, if a connection consists of fewer parts, it will probably be easier to manufacture. Then other aspects have to be considered as well; these are however not treated in this master's project.

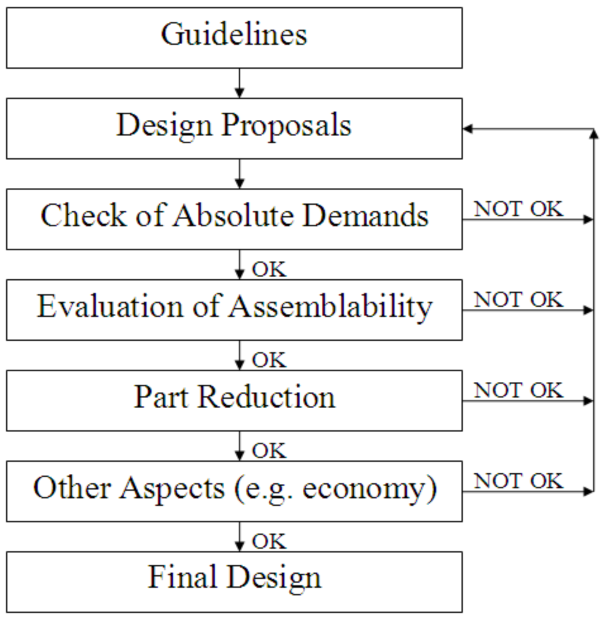


Figure 5.1 Design procedure for the developed method.

5.3 Guidelines for Structural Connection Design

In this section guidelines for connection design in industrial construction will be presented. The aim for the guidelines is to help the designer to develop new connections for industrial construction that are easy to assemble. Some of the guidelines are inspired by the methods in Chapter 3 and some are general knowledge. Some of the guidelines will be further described and used in the evaluation, see Section 5.5.

Appearance: Connection details should not be visible in the final building if they are judged to reduce the esthetical value.

Construction environment: Production and assembly should be performed in a controlled and dry environment.

Costs: Element and their connections should be as cost effective as possible both regarding manufacture and assembly.

Crane time: The crane time needed for each element should be kept to a minimum.

Ergonomics: Production and assembly should be planned to improve the workers ergonomics.

Fixation methods: Only clean and dry fixation methods should be used and not connections methods such as welding and grouting.

Fixation: Connections should be easy to fixate by as few operations and assembly workers as possible.

Maintenance: Connections is preferred to be designed for a small need of maintenance. If maintenance is needed it should be easy to perform, e.g. regarding access.

Multipurpose connections: Connections are preferred to be used for other purposes than load bearing in the service state, e.g. used as lifting points during assembly.

Number of parts: The number of loose parts used in connections should be kept as low as possible.

Prefabrication grade: Elements are preferred to be fully prefabricated; no, or only little, supplementary work should be needed.

Stability: Elements should be stable as soon as possible.

Symmetry: Loose connection parts should be made as symmetrical as possible.

Temporary supports: Temporary supports should be avoided.

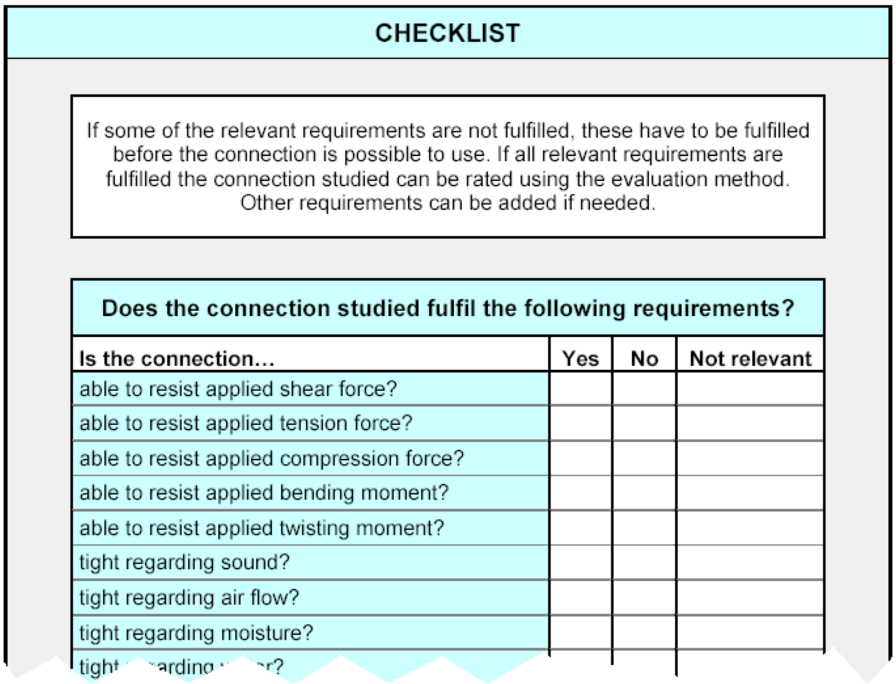
Tolerances: Connections' tolerances should be well adopted to their building system and easy to adjust.

Tools: The number of tools needed for assembly should be kept to a minimum. Large and heavy tools should be avoided.

5.4 Absolute Demands

It does not matter if a connection is easy to assemble if its absolute demands are not fulfilled. Thus it is important to check that all absolute demands are satisfied. These demands are however not the same for all connections. Depending on which type of structure and where in a structure the connection should be placed, the demands can vary significantly. For instance, demands concerning temperature and tightness might not be as important in a car park as it is in a residential building. For this reason, a product specific list, containing all absolute demands, has to be checked specifically for each situation.

In order to check the performance of possible connections a checklist has been developed, as introduced above. The checklist should be used to check that the connection fulfils its absolute demands. Three answers can be made for each demand; *Yes*, *No* or *Not relevant*. The three alternatives are chosen in order to make the checklist flexible so it can be used in different situations. An extract from the checklist is shown in Figure 5.2, while a total checklist is presented in Appendix A. This list can, however, be increased with other demands if needed. If all answers in the checklist are *Yes* or *Not relevant* the next step in the method can be carried out. If any demand in the checklist gets the answer *No* the connection can not be used and the designer must change the design of the connection, chose another design or consider to change the system.



CHECKLIST

If some of the relevant requirements are not fulfilled, these have to be fulfilled before the connection is possible to use. If all relevant requirements are fulfilled the connection studied can be rated using the evaluation method. Other requirements can be added if needed.

Does the connection studied fulfil the following requirements?

Is the connection...	Yes	No	Not relevant
able to resist applied shear force?			
able to resist applied tension force?			
able to resist applied compression force?			
able to resist applied bending moment?			
able to resist applied twisting moment?			
tight regarding sound?			
tight regarding air flow?			
tight regarding moisture?			
tight [illegible]			

Figure 5.2 Extract from the checklist of absolute demands.

5.5 Assemblability Evaluation Method

The evaluation handles the assemblability of connections. The result should give the designer enough information about different connections in order to decide which connection is the most favourable in the actual situation. It shows which properties that could be improved in order to ease the assembly even more. The evaluation is based on criteria related to assembly. The evaluation do not present the result related to costs, but give an assembly index, which is a qualitative grade, on each studied connection. The evaluation can be seen in Appendix A, and in the following sections the structure of the evaluation and the criteria used in the evaluation will be presented.

5.5.1 Evaluation Structure

The evaluation is mainly inspired by the DFA2 method described in Section 3.8, but the criteria have been developed to suit connection design in building industry. The criteria are based on the guidelines and methods presented in Chapter 3 and they are further discussed in the next section. Each criterion in the evaluation is given three statements at different levels; desired, acceptable and unacceptable. The designer should then decide which statement that is best suited for the studied connection. The number of statements has been limited to three in order to make the evaluation easy to use, as discussed in Section 5.1. Under the statements there are an empty box for adding comments and assumptions which justify the choice.

Each statement in the criterion is given a point, p, related to the level; 3 points (p_{max}) for desired, 1 point for acceptable and -1 point (p_{min}) for unacceptable. These points have been verified with the case study, further described in Chapter 6, and they are recommended not to be changed. The point range has been chosen in order to emphasize the difference in the statements, e.g. the negative point for the unacceptable statement (p_{min}) is chosen in order to emphasise the negativity. Furthermore, in order to weight the criteria to each other, every criterion are given an importance factor, I. The factor is set to one of three levels, depending on the relevance of each criterion; 0 for not relevant criteria, 1 for relevant criteria and 2 for extra important criteria. However, it is important to use the same factor for equal design situations in order to be able to compare different connections. It is also important to stress that the factors are based on the situation in which the connection should be placed. Finally, a grade, G, is calculated for each criterion as the importance factor times the point of the criterion, see Equation 5.1.

$$G = I \cdot p \qquad (5.1)$$

The result of the evaluation is shown both for each criterion separately and for the studied connection as a whole. On the result page a summation with importance, point and grade for each criterion is presented in order to give the user an overview. The negative grades are marked red in order to get the users attention and highlight the criteria that can be improved. In addition, criteria with good grades are marked green. The number of criteria used (criteria with importance factor 1 or 2) are also presented. For the studied connection a mean grade, G_{mean}, and an assembly index, A, are calculated. The mean grade is calculated as the sum of the criteria grades divided by the sum of the importance factors, see Equation 5.2. Of course, the calculation could be made by dividing the sum of the criteria grades by the number of questions. However, the chosen calculation is made in order to take the importance into account and it results in a mean value between -1 (p_{min}) and 3 (p_{max}). The assembly index is calculated as the quotient of the mean grade minus the minimum point and the maximum point minus the minimum point, see Equation 5.3. The assembly index is presented in percent with the best value of 100 % and the lowest of 0 %. The connections can then be compared to see which connection had the best assembly index. The designer can then choose which connection to use or make changes in design and start over checking absolute demands and redo the evaluation.

$$G_{mean} = \frac{\sum G}{\sum I} \qquad (5.2)$$

$$A = \frac{G_{mean} - p_{\min}}{p_{\max} - p_{\min}} \qquad (5.3)$$

The evaluation is preferred to be performed in an Excel-document where all the equations are included in the file. The grade for each criterion will than be calculated automatically. Warnings for errors are included in the file. There are warnings if more then one statement are chosen, shown in Figure 5.3, and if no statement is chosen, shown in Figure 5.4.

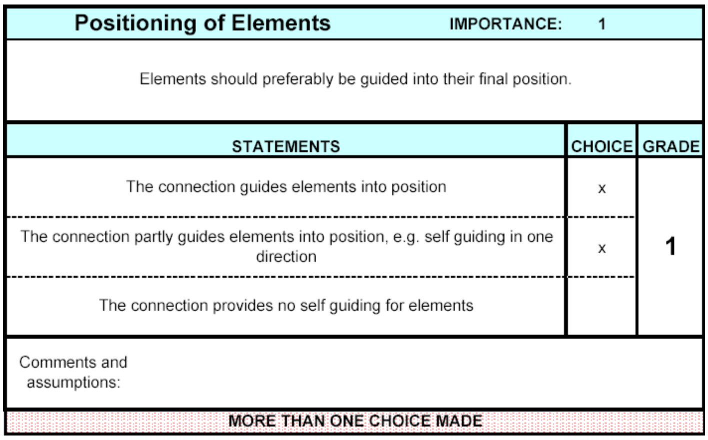


Figure 5.3 Warning in the evaluation; more than one choice are made.

Stability	IMPORTANCE: 1	
Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provide stability at once		-
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		
Comments and assumptions:		
MAKE A CHOICE		

Figure 5.4 Warning in the evaluation; no choice are made.

5.5.2 Evaluation Criteria

In this section the criteria used in the evaluation will be presented. Each criterion is discussed separately and choices are explained. The purpose is to give an understanding of the criteria and why those have been chosen. Some of the criteria are mentioned in Section 5.3 but here they will be presented more in detail.

Stability

For industrial construction, temporary supports should be avoided as long as possible. This is an extension of the guideline for precast concrete, Section 3.2.2, where temporary supports are allowed but should be prepared. Each element should preferably be stable as soon as it is put in position. The connections used to hold an element in place could for instance be made moment resistant to avoid the need for extra supports. However, the connections might be more complex and require even more time for assembly than the time used for temporary supports. The connection might also be more expensive to manufacture. The most desirable connection should eliminate the need for temporary supports but not be too complex to manufacture or to assemble. To achieve this, the designer has to perform a manufacture analysis. Stability is important regarding crane time, which should be kept to a minimum. For that reason, stability at once has been decided as the optimal solution. If the element is stable after a small fixation or adjustment it is acceptable, but if major fixation operations or temporary supports are needed the lowest point will be given.

Positioning of Elements

In order to make the assembly easier, connections are preferred to self-guide elements into their final position, which is discussed in Section 3.4. Self guiding refers to the connections ability to self align and self locate elements. This is extra important if the precision of the lifting devise is not very exact. This is also important regarding working environment. A connection that guides an element into position is the best solution and no self guiding is the worst solution. Connections that are partly self guiding, e.g. guide an element only in one direction, are given the mean point.

Positioning of Loose Parts

Also loose connection details should be self guiding as these should be assembled to the connection. A connection can exist of several loose details, if all these are self guiding the highest point is given. If some loose details are self guiding it is acceptable and if no self guiding is provided the lowest point will be set.

Number of loose parts

Many connection are designed containing lose parts, such as pins and bolts. Handling of loose parts can be time consuming; therefore the loose connection parts needed during assembly should be as few as possible, see assembly guidelines in Section 3.3.2. To be able to evaluate connection types correctly, subassemblies are defined as one part. One subassembly can be a threaded rod with two bolts delivered to the assembly site in one piece. Since most connections have at least one loose part, one or no loose parts have been defined as the best solution. Moreover, connections containing two or three loose parts are given the mean point and connections including more than three loose parts are given the lowest point in the evaluation.

Size of Loose Parts

As mentioned above handling of loose parts can be time consuming. As well as the number of loose parts, the geometry of these parts is important. Long or wide loose parts that are hard to handle should be avoided. With help of the DFMA method described in Section 3.3, an estimation of size intervals has been made for building industry. A part between two and thirty centimetres is graded highest while a length between one and two centimetres or thirty to a fifty centimetres is on an acceptable level. However, sizes under one centimetre and parts over fifty centimetres are hard to handle, therefore treated as unacceptable in the evaluation.

Weight of Loose Parts

Also the weight of loose parts has to be considered. Too heavy parts result in a more difficult assembly. Here weights below one kg are valued highest and weights between one and three kg are considered acceptable while weights over three kg are chosen to get the lowest point. The estimations of weight intervals have been based on experiences.

Need for Assembly Workers

In industrial construction the assembly work should preferably be possible to perform by workers without special skills. Special skills are in this project defined as welding skills or similar. Of course all assembly workers have to know how to assemble the system. Furthermore, the number of assembly workers should be minimised. Every operation should preferably be performed by only one worker. The number of workers is defined as the number of workers in addition to the crane operator. If an assembly can be performed by only one worker with no special skills the highest point will be given. If two workers without special skills are needed it is acceptable in the evaluation. Finally, a need of more than two workers or workers with special skills is under the acceptable level.

Safety for Workers

In addition to the number of assembly workers, the evaluation treats safety for the assembly workers. The risk for workers getting injured in an assembly process should be minimised. In this evaluation only injuries related to the connections are considered. In the evaluation connections are judged depending on the risk workers are exposed to while performing an assembly.

Tools

At the construction site, or assembly site, operations are performed in different locations. If ungainly tools are needed, the assembly operation and movement of these tools will be difficult. Equipment that needs extra power sources, e.g. air tools, should be avoided as long as such do not reduce assembly time remarkably. The designer has to consider whether the time reduction for a curtain tool is sufficient or not. Further on, it is also beneficial that the number of tools needed is kept to a minimum. Therefore the optimal solution is if not more than one small tool is needed. If two or three small tools are needed it is acceptable while a need for many small tools or heavy, large or ungainly tools are under the level of acceptance.

Accessibility

During assembly it is important that connections are accessible for the workers, which is discussed in Section 3.3.2. It should be avoided to place connections in tight sections or outside the building at high levels, in order to improve the workers ergonomics. It is also considered if a connection has to be handled from more than one side. If the access is restricted there is a risk for lacking quality. Therefore, handling needed from one side only with easy access is the optimal solution. Easy access with handling needed from two sides is considered to be acceptable while restricted access or handling needed from more than two sides is under the acceptable level.

Fixation Method

Fasteners should be designed as simple as possible, previously discussed in Section 3.3.2. In industrial construction no unclean fixation methods, such as welding and grouting, are acceptable. Therefore such fixation methods must get the lowest point in the evaluation. On the other hand, snap fits that lock the connection instantly or fixation with a simple motion are considered to be the best fixation method. Fasteners consisting of screws or a combination of motions are in the evaluation considered to be acceptable, giving the mean point.

Protruding Parts

When handling an element during assembly it is important that its connections do not damage components, protruding parts, connections or personnel, as described in Section 3.2.2. Connections which could be damaged have to be protected. This can be accomplished by making the exposed details less fragile or by protecting them in some way. The best solution is a connection which is not harmful to elements or fragile itself. If damage is possible it is important to define how large the damage is. Of course, a damage that is easy to repair is better then a damage that is difficult to repair or that require exchange of a whole element. Yet, a connection that is harmful or fragile is not a desired solution in industrial construction.

Multi-Purpose Connections

Connections used for more than its main purpose, called multi purpose connections, can increase the efficiency of an assembly. One application, useful for the assembly process, is integrated lifting devices in the connections which are treated in the evaluation and discussed in Section 3.7. Additionally, it is important that the elements hang straight when lifted. The best solution needs no changes to serve as lifting devise while a connection that serves as a lifting device with help of some extra equipment is acceptable. If the connection does not serve as lifting device the connection gets the lowest point.

Fool Proof

Connections should be hard to misassemble. Parts should, for example, only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose. As a result, correctly designed connections will decrease the number of possible errors during assembly. Therefore, a connection easily misassembled is rated under the acceptable level. Connections with some actions made to prevent misassembly are acceptable while connections impossible to misassemble are given the highest point in the evaluation.

Demountability

The environmental effects are important to handle in industrial construction. Buildings should rather be disassembled then demolished after service life. As a result, a disassembled building can be recycled or reused. It can also be necessary to replace an element during service life. Furthermore, the ability for disassembly depends to a large amount on the connections of the elements. A connection is considered to be best if disassembly is possible without causing damage to elements or connections themselves. Disassembly causing damage to connections but not to elements is acceptable in the evaluation. However, if only demolishment is possible it is under the acceptable level.

Tolerance

As discussed in previous chapters, tolerances are an extensive question in industrial construction as well as in any construction. It is hard to define tolerances in exact numbers as it depends on the system. In order to be able to use the evaluation for different systems the criteria refers to the ease to adjust after set tolerance limits. Therefore, connections that adjust automatically when assembled are desired. Connections easy to adjust are acceptable while connections hard to adjust or require extra time is unacceptable.

5.6 Minimising the Number of Parts

When the previous steps in the method are performed and the designer has decided which connection to use, the final step can be carried out. The purpose of this step is to eliminate all unnecessary parts in the chosen design in order to make it even easier to assemble. The method used to reduce parts is the one developed by Boothroyd *et al.*, see Section 3.3.3. The same method is also used by Lassl and Löfgren (2006). The questions for part reduction are for convenience repeated here. If a connection part gives negative answer to all of the three following questions it could be combined with another part.

- Does the part move relative all other parts?
- Must the part be of another material than other parts?
- Must the part be separated from other parts, or else one or more of the other parts' assembly will be impossible?

An example of a part reduction with help of these questions is shown below. The example was first presented by Lassl and Löfgren (2006). In Figure 5.5 and Table 5.1, an example of a connection is presented. The connection intends to connect a wall element to a column; it will however not be further described in its context. The three questions are then answered for each part and the ones that are able to combine or eliminate will be identified. The connection after part reduction is shown in Figure 5.6 and Table 5.2 and it can be seen that the connection is simplified and have fewer parts.

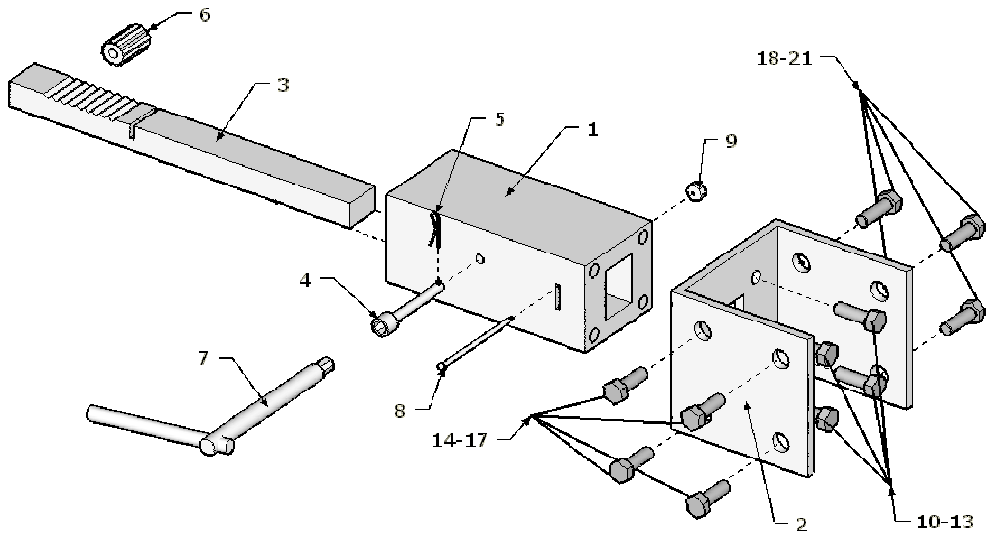


Figure 5.5 Example of a connection before part reduction, Lassl and Löfgren (2006).

Table 5.1 Description of the parts used in Figure 5.5.

Part #	Part description
1	Stock tube, main container
2	Mounting plate
3	Revolver
4	Rotating axis
5	Wedge (locks 4&6 in place)
6	Gearwheel (mounted on part 4)
7	Handle (inserted into 4)
8	Screw (locks revolver)
9	Nut (mounted on revolver)
10-13	Screws (fastening mounting plate on stock tube)
14-17	Screws (fastening mounting plate on wall element)
18-21	Screws (fastening mounting plate on wall element)

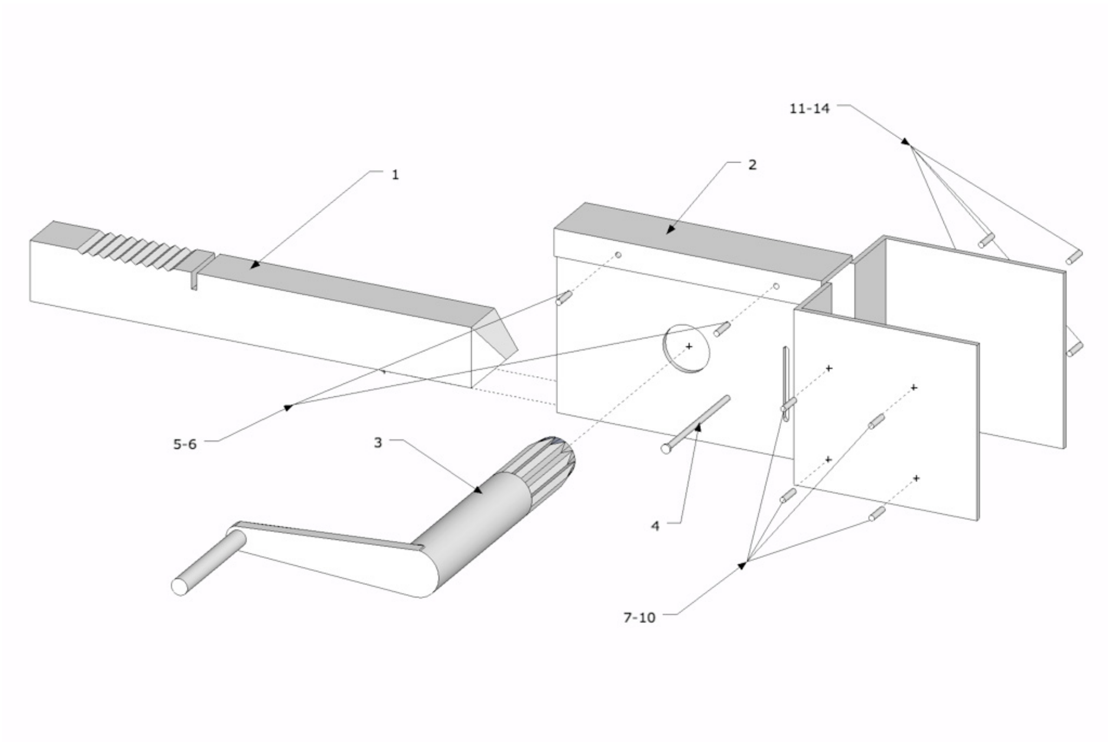


Figure 5.6 Example of the connection after part reduction is performed, Lassl and Löfgren (2006).

Table 5.2 Description of the parts used in Figure 5.6.

Part #	Part description
1	Revolver
2	Sheet metal box
3	Handle with cogs
4	Plastic snap fit plug
5-6	Rivets (holding the box together)
7-10	Rivets (fastening the box on wall element)
11-14	Rivets (fastening the box on wall element)

5.7 Other Aspects

Several other aspects, besides assembly, have to be considered before a final design is chosen. Manufacture, accessible material resources, overall economy, durability, partnering organisations and producers are examples of such aspects. In Figure 5.7 design for assembly is shown as one of several areas that all influence the design of structural connections in industrial construction. These aspects are not considered in this project but they are however important to take into consideration when designing connections.

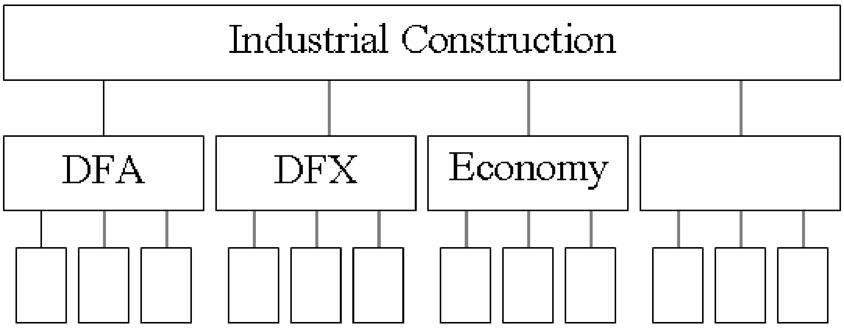


Figure 5.7 Assembly is one area besides for example manufacture and economy that all are a part of industrial construction.

6 Case Study

A case study has been performed in order to improve and test the evaluation step of the design method during its development. Several connections were tested in the study. There was no interest to improve the connections themselves but the case study was aimed to check, calibrate and improve the evaluation method only. Different versions of the evaluation method have been tested resulting in the final evaluation method described in Section 5.5.

This chapter starts with a presentation of the connections tested in the case study including their assumptions. This is followed by a presentation of criteria which have been rejected from the method during the case study. The rejected criteria can still be seen as guidelines when designing structural connections. Finally, results from the case study will be presented and discussed. The result presentation will include results from the final method only. However, tested point ranges and different importance factors will be discussed.

6.1 Evaluated Connections

Several connections of different types were tested. The connections used in the case study are described below with figures, explanations and assumptions. The purpose is to give a quick overview and not to give full knowledge of each connection. All connections presented have been evaluated using the different versions of the evaluation method during its development and the results were compared. Some of the connections studied are industrial connections while others are not at all industrial. The different grades of industrialisation were chosen in order to see if different connections gave expected varying results. The connections were iteratively tested in order to see the result changes for different changes in the method.

Consolis Floor-to-Floor Connection

The connection is used between concrete elements in a building system developed by Consolis (2007), see Figure 6.1. The connection in the study is a floor-to-floor connection but the same connection can also be used for wall-to-wall connection, this situation is however not treated in the study. Each connection consists of steel plates cast into the elements where the connection is located. The connection is locked by a treaded bar and two nuts fixating these steel plates. To ease the assembly the bar and the bolts are assumed to be preassembled; delivered to the assembly site as one part. It is also assumed that this connection is not used as a point for lifting as other connections in the same element are more suitable for connecting a lifting devise.

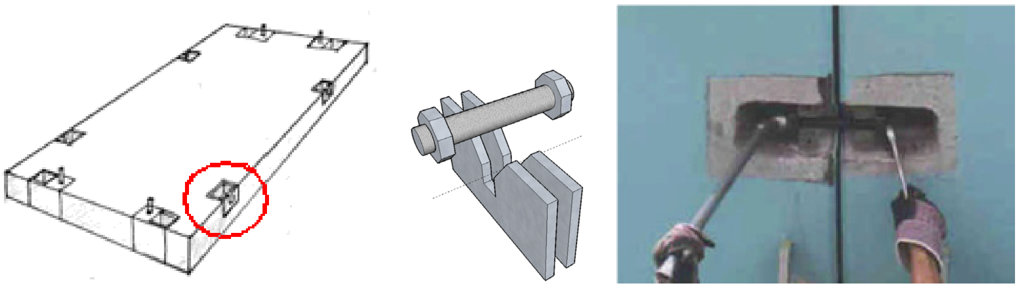


Figure 6.1 Floor-to-floor connection for concrete elements, Consolis (2007).

Consolis Wall-to-Floor Connection

This connection, shown in Figure 6.2, comes from the same system as the floor-to-floor connection above developed by Consolis (2007). This connection is used both when a wall element is placed on top of a floor element and when a floor element is placed on top of a wall element. However, the study only handles the second of these cases. The connection consists of a steel box that is cast into concrete elements in a factory. A bolt from one of the steel boxes in an element underneath is fixed with a nut in the steel box in the element above. This connection is assumed to serve as a lifting point if a bolt is placed on the rod.

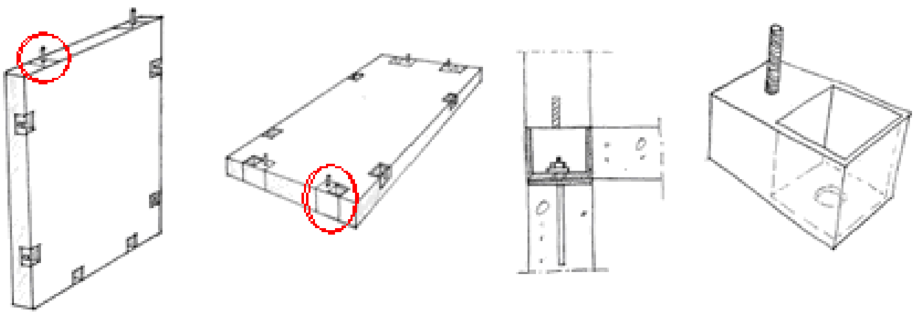


Figure 6.2 Connection used to connect floor elements to wall elements, Consolis (2007).

Concrete Beam-to-Column Connection

The beam-to-column connection, shown in Figure 6.3, is used for prefabricated concrete elements and is adopted from Betongvaruindustrin (2005). The beam is slipped on to a treaded rod that is precast into the column. On the topside of the beam the connection is fixed with a nut. The hole in the beam is assumed not to be filled with concrete which is a possibility.

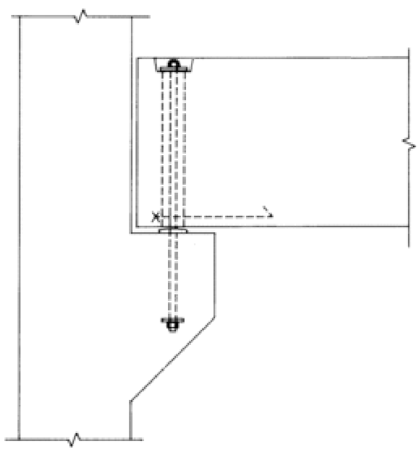


Figure 6.3 Prefabricated concrete beam and column connected with a bolt, adopted from Betongvaruindustrin (2005).

Steel Beam-to-Column Connection

The connection consists of standard hot-rolled steel beams fixed together with nuts and bolts, see Figure 6.4. The connection is adopted from SBI (1988). A steel plate with predrilled holes is welded to the end of the horizontal beams in a factory. Also the vertical beam have predrilled holes were the horizontal beam is to be fastened.

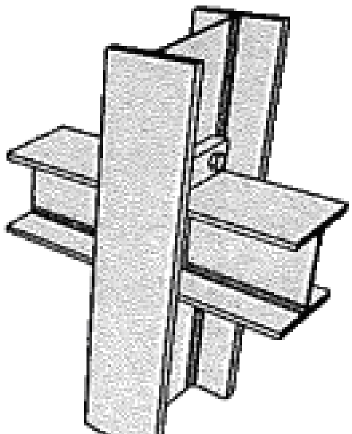


Figure 6.4 Bolted hot rolled steel beams, adopted from SBI (1988).

Concrete Cast in-situ Connection

This connection is a joint between prefabricated concrete floor elements and a prefabricated concrete wall or beam, see Figure 6.5. Extra reinforcement bars are added and concrete is cast in situ in order to make the connection fixed. No extra supports are assumed to be needed before the concrete is cast.

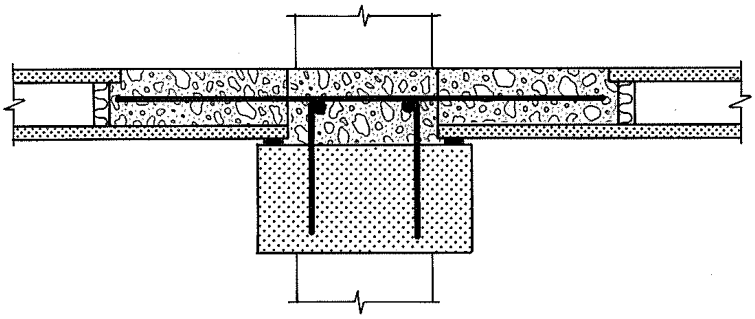


Figure 6.5 Connection for prefabricated concrete elements, connecting two floor elements upon a beam, from FIP (1988).

Beam with Movable Steel Plate

The connection consists of a beam hooked to a column with help of a movable steel plate, see Figure 6.6. The connection is developed by Spenncon AS and is published in *fib* (2007). The connection is assumed to be made of steel cast into concrete elements. It is supposed that the hook is easy to slide horizontally without any need for tools. The purpose with the movable hook is the possibility to lift the beam in place before sliding out the hook into the column which decreases the risk of jamming and damage of the connection detail.

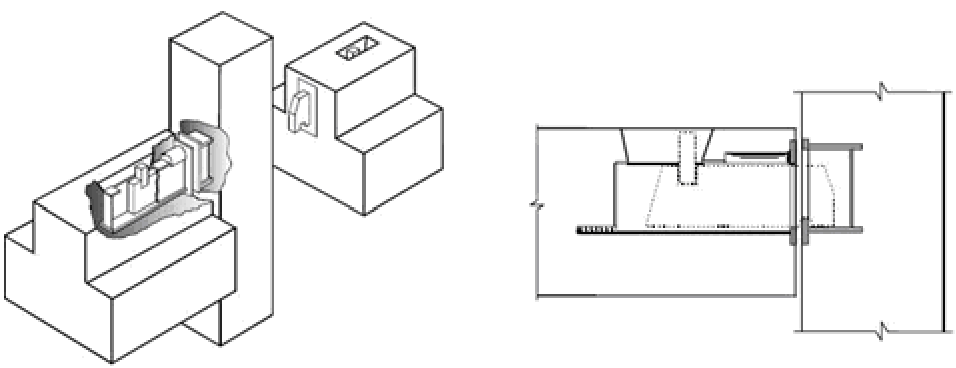


Figure 6.6 Movable steel plate connecting a beam to a column, published in fib (2007).

Welded Connection of Steel Beams

A welded connection of two hot-rolled steel beams is shown in Figure 6.7. The plate between the beam ends is assumed to be welded to one of the beams in a factory and only needs to be welded to the other beam on site. Welding require workers with special skills. With rightfully preformed welds, the connection will be very stiff. The assembly of the connection is however weather sensitive; rain and wind can be harmful.

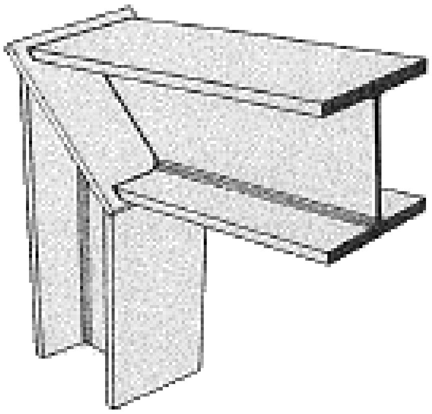


Figure 6.7 Steel beams connected by welds, adopted from SBI (1988).

Timber Connection with Dowels

This timber connection consists of two timber members joined together with steel dowels, see Figure 6.8. There is also a plate inserted in the connection through which the dowels are placed. The plate increases the stiffness of the connection which can be a problem in wood connections.

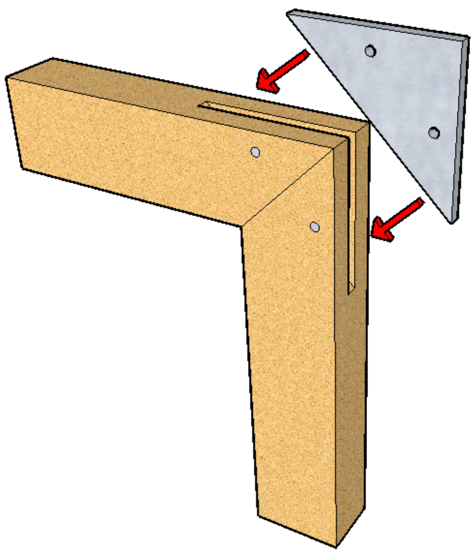


Figure 6.8 Timber connection with steel dowels.

Roller Bearing for Volume Elements

The connection, shown in Figure 6.9, is used between volume elements, and is developed by Setra Group (2007). The connection consists of three parts; a cylinder which is loose and two other details which are attached to the elements in a factory. At the assembly site the cylinder is placed on the lower element just before the next element is put in place. The connection cannot resist tension in the vertical direction but it is assumed to be stable thanks to the self weight of the elements above. If not, the tensile forces have to be resisted in another way.

Figure 6.9 Roller connection for volume elements, adopted from Setra Group (2007).

Connection for Storage Rack

In Figure 6.10 a storage rack is shown. The connection studied is where the beam is attached to the column shown in the figure. There are holes in the column into which the beam can be hooked on to. The only tool assumed to be used is a hammer.

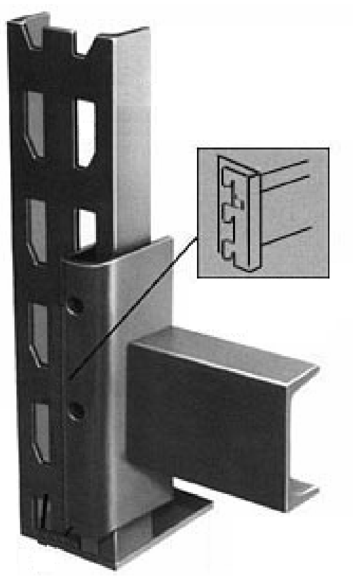


Figure 6.10 Connection of beam and column in a steel storage rack, Jarke (2007)

Beam Shoe

The connection detail is used when fastening a timber beam to a wall or a column. It consists of a bent steel plate fixed using nails, see Figure 6.11. It is assumed that the beam shoe is already fastened to the wall or column before the timber beam is lifted in place.

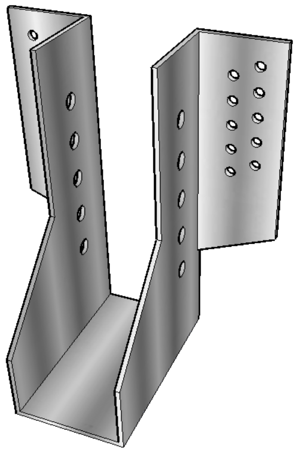


Figure 6.11 A beam shoe used to connect a timber beam to a wall or a column.

6.2 Results

As described above, all connections have been tested during the development of the evaluation method and the case study has been performed in order to check, calibrate and improve the design method only. In this section, results from the final evaluation method will be presented and discussed. The results from previous versions will not be presented in the thesis. Motivations for the structure and the grading system will however be included.

6.2.1 Result Presentation

The results for each connection are presented in Table 6.1 and the total case study is presented in Appendix B. In the table, it can be seen that a connection with low prefabrication grade or with a complex assembly gets a low assembly index. The concrete cast in-situ connection, for example, which is quite complex to assemble, gets an assembly index of 16 %. The roller bearing connection for volume elements gets, on the other hand, an assembly index of 88 %. All other connection handled in the case study get assembly indexes scattered between these values. The results represent the ease of assembly in a realistic manner as good designs were given a good result and vice versa. This indicates that the most important areas regarding assembly are handled in the evaluation. It is however important to stress that the connections in the table should not be compared to each other as they are used in different situations. When two or more connections should be compared, it is critical that they are evaluated in the same location in the system and have the same importance factors of the criteria. Only then can the connections be compared. This is the case for all beam-to-column connections as they are, due to the same situation, given the same importance factors.

Table 6.1 Summation of the results from the case study of the final evaluation method.

RESULT FROM CASE STUDY	Consolis Floor-to-Floor Connection	Consolis Wall-to-Floor Connection	Concrete Beam-Column Connection	Steel Beam-to-Column Connection	Concrete Cast in-situ Connection	Beam with Movable Steel Plate	Welded Connection of Steel Beams	Timber Connection with Dowels	Roller Bearing for Volume Elements	Connection for Storage Rack	Beam Shoe
Number of Criteria Used	13	16	16	16	15	13	13	16	16	13	16
Mean Grade	2,33	1,45	1,45	1,09	-0,37	2,47	-0,26	1,13	2,53	1,77	1,09
Index	83%	61%	61%	52%	16%	87%	18%	53%	88%	69%	52%
Stability	-	3	3	1	3	1	-1	-1	3	1	3
Positioning of Elements	-	-2	-2	-2	-1	2	-2	-1	6	1	-2
Positioning of Loose Parts	3	-1	-1	-1	-1	-	-	-1	3	-	-1
Number of Loose Parts	3	2	2	-2	-1	6	6	1	3	3	-2
Size of Loose Parts	3	3	3	3	-1	-	-	3	3	-	3
Weight of Loose Parts	3	3	3	3	1	-	-	3	1	-	3
Need for Assembly Workers	3	6	6	6	-2	6	-2	3	3	3	6
Safety for Workers	1	1	1	1	-1	3	-1	3	1	1	1
Tools	2	6	6	2	-2	6	-2	3	3	3	6
Accessibility	3	3	3	1	-1	3	-1	1	3	3	1
Fixation Method	2	2	2	2	-2	6	-2	1	3	1	2
Protruding Parts	3	-2	-2	6	2	6	2	3	3	3	2
Multi-Purpose Connections	-	1	-1	-1	-	-1	-1	-1	-1	-1	-1
Fool Proof	3	1	3	1	-1	3	-1	1	3	1	1
Demountability	3	3	3	3	-1	3	-1	1	3	3	1
Tolerance	3	3	3	1	1	3	1	-1	3	1	1

Further on, the table shows which areas (criteria) that get low grades and therefore have to be considered in a redesign, if a connection should be improved. Also good results are highlighted in the summation. For all criteria, varying statements are chosen for the tested connections, which confirm the accuracy of the criteria. Some criteria in the early versions of the evaluation gave the same result for all studied connections. These criteria were, partly for this reason, rejected from the evaluation method. They are however described in the next section. As can be seen in the table, the criteria concerning multi-purpose connections get the same result for most of the studied connection. However, this due to the amount of non-industrial connections in the case study and the criteria is still judged as important to keep in the evaluation.

There are totally sixteen criteria in the final evaluation method. There were at the most three criteria that were considered not to be relevant for the studied connections. The criteria handling loose parts were irrelevant for the connections that did not consist of any loose parts. They were on the other hand relevant for the other connections. All criteria were however relevant for most of the connections. None of the criteria were irrelevant for more than three of the eleven studied connections.

6.2.2 Structure and Grading

The structure of the evaluation method is, as mentioned before, inspired by the DFA2 method which is based on criteria handling several assembly areas. This structure was chosen because it is simple and systematic and easy both to follow and to use. The other studied methods are based on assembly operations and their time consumption and cost. If such a method should be developed for structural connections in building industry, all relevant operations has to be identified and given an assembly time and cost.

In the evaluation method described in Section 5.5.1, importance factors are used to balance the criteria. Several different importance factors have been tested during development of the evaluation method. In the first versions of the method, no factors were used. It was however decided that all different criteria were not equally important in every situation, so a system using importance factors were introduced. With help of the importance factors the magnitude of each criterion could be decided. When importance factors were introduced in the method, it was possible to set factors from zero, for not relevant, up to three, for very important criteria. It showed however that the highest factor, the factor three, gave a too large impact on the result of the evaluation. Because of this lack of balance in the evaluation, the importance factor three was removed. As an extra result of this the importance factors became easier to choose, as only three options remained; irrelevant, relevant and extra important. If the importance factor two is chosen for a criterion, the criterion will affect the result twice as much as it would with a factor one. This means that if all sixteen criteria are relevant, i.e. given the importance factor one, each criterion will affect the result by one sixteenth. However, if one of the criteria is given the importance factor two, this criterion will affect the result by two seventeenth and all other criteria affects the result by one seventeenth.

Also the criteria points, given for each statement, have been tested in the case study. In the DFA2 method, see Section 3.8, a point scale of 1, 3 and 9 was used. This was considered for the new method as well, however, the negative point for unacceptable statements was considered more important as it stresses the negative effect of the statement. Therefore, in the first evaluation version the point scale minus one, one and four were used. These points appeared to give quite good results except for the highest point. Point four appeared to affect the result too much. So, only the highest point was changed from four to three. This resulted, as described in Chapter 5, in criteria points set to minus one point for unacceptable, one point for acceptable and three points for a desirable solution.

6.3 Criteria and Guidelines Rejected from the Evaluation

It is, according to Section 5.1, important that the method is user friendly and that it is not too extensive. Therefore irrelevant criteria should be avoided. Here are some criteria described that were rejected during the case study.

Symmetry

Many of the studied methods in Chapter 3 recommend symmetrical parts. In building industry, however, most elements are asymmetrical in order to fit their position in the final product. An external wall is, as discussed in Section 4.1, of course not equal on the inside and on the outside. On the other hand, symmetry can be favourable for connection details such as pins and dowels. But if details like these are used they are always symmetrical in some extent. Further on a whole connection can be symmetrical which off course is favourable. This is however more important when an element should be produced, as the same connection could be mounted in different directions and positions.

Sticky, Slippery etc

The case study resulted in that no connections were sticky, slippery or hot. As all studied connections gave the same result this criteria were rejected. This was done in order to keep the number of criteria low as this will ease the use of the evaluation. Some of the ideas from this subject were instead treated in the criterion concerning protruding parts and damage.

Special Tools

During development of the method it was first decided that special tools should be avoided. But later it was determined that such tools could be favourable if these reduces the assembly time. The tools should however not be ungainly to use or move on the assembly site.

Unintended Disassembly

In industrial construction, connections might be possible to demount. Connections must however be designed to eliminate the risk of being demounted, by e.g. a user, during service life. This was first handled in a criterion in the evaluation method but during the case study the subject was however decided to be handled in the checklist for absolute demands. As an unintended disassembly would be devastating, this cannot be treated as a desired property.

Tolerances

In the evaluation method tolerance is graded depending on the connections ease to adjust within its tolerance range. It has been considered to instead grade tolerance on the basis of tolerance intervals. A connections tolerance interval is however decided depending on its system and it is therefore necessary to fulfil the prescribed tolerance. So, fore this reason, the control of tolerance interval is performed in the checklist for absolute requirements while the ease for assembly depending on a connections tolerance is handled in the evaluation method.

7 Conclusions

In this chapter conclusions of the project are drawn. This is followed by a comparison of the result and the aim of the project, which is described in Section 1.3. Finally, suggestions for further studies are presented.

7.1 Conclusions of the Project

There are both differences and similarities between manufacturing industry and building industry. The methods used in manufacturing industry are focused on assembly of small details in a suited workstation. Many guidelines could however be adjusted into the developed method for connection design in industrial construction. The new method works as intended for evaluation and control of structural connections, according to the case study presented in Chapter 6. It gives a relative grade and an assembly index for each connection and troublesome areas in a studied design are highlighted. It is possible to ease the assembly by improving both the connection itself and the building system. The method does however not give a time or cost estimation which could be useful. So if this is wanted, the method has to be further developed.

In the evaluation sixteen criteria were used. In the case study it was shown that at the most three of these were considered not to be relevant of the studied connections. All criteria were however relevant for most of the connections. None of the criteria were irrelevant for more than three of the eleven studied connections.

In the evaluation, some of the criteria are exact and precise while others handles personal opinions. It is easy to choose the correct statement of the exact criteria but the evaluative ones can be more troublesome. Different designers might have different opinions concerning a certain connection or design aspects, therefore different choices can be made. It is therefore important to evaluate well defined connections in order to get a reliable result. The statements can also be apprehended individually by the designer. This is prevented by providing the possibility to write assumptions and motivations for the choice of statement. The most comparable results are however achieved if the same designer fills in the evaluation form for all connection that should be compared. The evaluation has been tested by experienced designers, and the results were the same for most criteria. When the results differed, this turned out to mostly be due to different apprehensions of the studied connection.

In the design method, all absolute demands have to be fulfilled if a connection should be possible to use. All absolute demands are however not always possible to fulfil; compromises might be necessary. The designer has to decide if it is possible to change the building system in order to make the absolute demands easier to fulfil.

Check of Huang's Functional Requirements

Most of the functional requirements presented in Section 5.1.2 are fulfilled by the design method, which can be seen in Table 7.1. All information concerning the studied connections is collected in the connection information page in the evaluation. The assembly performance is measured by choosing statements. Whether or not a design is good enough is not directly determined by the method as the assembly index varies for different connection types. However, it is possible to use the result as a decision basis when deciding if a connection is good enough. Furthermore, it is possible to compare design alternatives which are aimed for the same building system and have the same function. Strengths and weaknesses are pointed out in the result page of the evaluation; good areas are marked green and problem areas are marked red. By controlling the statements for each criterion it is possible to see why an area is strong or weak and improvements can be performed in order to achieve the best statement. It is also possible to see how the assembly index changes for a certain redesign, but the choice of statement in the modified criteria has to be changed in order to see the effect. The method does not carry out improvements by itself but an iterative evaluation procedure can be used for design changes.

Table 7.1 Summation of the fulfilment of the requirements on a design method, which are presented in Section 5.1.2.

Basic Functions	**Fulfilled**	**Not Fulfilled**
Gather and present facts	X	
Measure performance	X	
Evaluate if a product design is good enough	X	
Compare design alternatives: Which design is better?	X	
Highlight strengths and weaknesses	X	
Advanced Functions	**Fulfilled**	**Not Fulfilled**
Diagnose why an area is strong or weak	X	
Point out how a design can be improved	X	
Predict "what-if" effects	X	
Carry out improvements		X
Allow iteration to take place	X	

7.2 Aim Verification

In the project several design methods used in manufacturing industry have been studied. The methods have been analysed in order to see if they are possible to use for connection design in industrial construction. Areas which could be used and areas which are not relevant for industrial construction were identified and discussed. The differences between manufacturing industry and industrial construction as well as the need for improvement of the methods were also discussed. Also guidelines used in building industry were handled and compared to guidelines used in the design methods. This corresponds to the first part of the aim from Section 1.3, repeated below:

- Investigate potential design methods in manufacturing industry and guidelines used in building industry. Identify their need for improvement in order to match connection design in industrial construction.

Further on, a design method for structural connections in industrial construction has been developed. The method consists of four parts: guidelines for industrial construction, a checklist for absolute demands, an assemblability evaluation method, and a procedure for part reduction. The design method was tested with help of a case study including eleven connections. This satisfies the second goal repeated below:

- Develop a design and evaluation method for structural connections in industrial construction, including case study verification.

7.3 Suggestions for Further Studies

The developed design method handles the assembly in industrial construction. However, as mentioned in Section 5.7, other aspects are important during connection design. Therefore further research is needed concerning these aspects. Furthermore, the developed method can also be improved as follows:

Quantitative method: The method developed in this project is, as earlier mentioned, a qualitative method. This means that design proposals are weighted and given a grade. A quantitative evaluation method giving an estimated time and cost for assembly could be preferred. In order to develop such a method, an extensive study has to be performed and a time bank has to be compiled. It would be useful to get an estimation of the cost saving and the pay-off time for a certain redesign.

Narrow methods: Another possibility is to have specified methods for each kind of connection, there could for instance be one version for wall-to-wall connections and one version for beam-to-column connections and so on. In this way, the method would be better suited for each type of connection and give more reliable results. The method would on the other hand be less general.

Interactive structure: The method could be improved using an interactive structure where irrelevant criteria automatically disappear. If there are no loose parts, for instance, the criterion handling properties of loose parts could be removed.

Design steps: Other areas could be added to the design method. The step concerning reduction of parts could, for example, be expanded also to minimising the number of assembly operations.

Evaluation of absolute demands: An evaluation concerning the absolute demands might be needed as it can be difficult to fulfil all absolute demands which might result in a compromise. It might be possible to use a similar structure for the absolute demands as used in the evaluation of assembly.

More connections: In this project eleven connections of varying industrialisation degree have been studied. More structural connections used in industrial construction could be tested in order to further develop the reliability of the evaluation method and improve it.

Limits for the assembly index: There are no specified limits for when a design is good enough or when it is acceptable. This is because the assembly index varies depending on the type of connection. The evaluation method might be possible to improve in such a way that it gives comparable results for different connection types. Another alternative is to make a larger case study in order to determine acceptance limits for different types of connections.

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APPENDIX A

Connection Design Method

Contents

1 Introduction

This design method addresses connection design in industrial construction. It is developed in the Master's Project *Connection Design for Easy Assembly*. The following document contains the method without any explanations and motivations of its structure. The method aims to help designers to design and evaluate structural connections which are easy to assemble. The method is preferred to be used in an Excel-Document but will here be presented as manual worksheets.

The design method is divided in four steps. Each step is presented in separately chapters but will be shortly described here:

Guidelines

The design method starts with guidelines that are presented in order to provide the designer with background information of connections design in industrial construction. This background information is aimed to help the designer to develop industrial connections that are easy to assemble.

Checklist for Absolute Demands

The next step is absolute demands; if a connection should be evaluated it is important to first make shore that the connection fulfils its absolute demands. These demands have to be fulfilled in order make the connection work properly, e.g. the load bearing capacity has to be fulfilled. The absolute demands are controlled with help of a checklist. If the absolute demands are fulfilled the next step in the method is to evaluate how well the connection is suited for assembly.

Assemblability Evaluation Method

The evaluation handles desirable demands, if these demands are neglected the assembly might be more difficult. The evaluation consists of criteria related to assembly which are divided into statements. The connection is graded depending on the chosen statement of each criterion. The result of the evaluation is an assembly index, which describes the connection's assemblability relatively, and a list of which areas that can be improved. The improvement can either be a change of the connection itself or the whole system. After the changes it is important to control if the absolute demands still are fulfilled. When a connection has satisfying result in the evaluation the final step can be performed.

Reduction of the Number of Parts

The last step in the design method concerns reduction of the number of parts in connections. The main reason for the part reduction is to make the assembly easer as fewer parts will result in an easier assembly. Besides, if a connection consists of fewer parts, it will likely be easier to manufacture.

2 Guidelines

Appearance	Connection details should not be visible in the final building if they are judged to reduce the esthetical value.
Construction Environment	Production and assembly should be performed in a controlled and dry environment.
Costs	Elements and their connections should be as cost effective as possible both regarding manufacture and assembly.
Crane Time	The crane time needed for each element should be kept to a minimum.
Ergonomics	Production and assembly should be planned in order to improve the workers ergonomics.
Fixation	Connections should be easy to fixate by as few operations and assembly workers as possible.
Fixation Methods	Only clean and dry fixation methods should be used and not connections methods as for instance welding and grouting.
Maintenance	Connections are preferred to be designed for a small need of maintenance. If maintenance is needed it should be easy to perform, e.g. regarding access.
Multipurpose Connections	Connections are preferred to be used for other purposes than load bearing in the service state, e.g. used as lifting points during assembly.
Number of Parts	The number of loose parts used in connections should be kept as low as possible.
Prefabrication Grade	Elements are preferred to be fully prefabricated; no, or only little, supplementary work should be needed.

Stability	Elements should be stable as soon as possible.
Symmetry	Loose connection parts should be made as symmetrical as possible.
Temporary Supports	Temporary supports should be avoided.
Tolerances	Connections' tolerances should be well adapted to their building system and easy to adjust.
Tools	The number of tools needed for assembly should be kept to a minimum. Large and heavy tools should be avoided.

3 Connection Description

INFORMATION OF THE STUDIED CONNECTION

To use the design method each method studied must be described. Fill in the connection description and add a connection picture below in order to make clear which connection that should be studied.

CONNECTION TITLE

INSERT CONNECTION DESCRIPTION HERE AND A TITLE ABOVE

PICTURE

INSERT CONNECTION PICTURE HERE

4 Absolution Demands

CHECKLIST

If some of the relevant requirements are not fulfilled, these have to be fulfilled before the connection is possible to use. If all relevant requirements are fulfilled the studied connection can be rated using the evaluation method. Further requirements can be added if needed.

Does the connection studied fulfil the following requirements?

Is the connection…	Yes	No	Not relevant
able to resist applied shear force?			
able to resist applied tension force?			
able to resist applied compression force?			
able to resist applied bending moment?			
able to resist applied twisting moment?			
tight regarding sound?			
tight regarding air flow?			
tight regarding moisture?			
tight regarding water?			
tight regarding heat?			
having tolerances suited to its system?			
able to resist chemical attack?			
able to resist fire?			
able to handle creep?			
able to handle shrinkage?			
stiff enough not to cause too large deflection?			
safe regarding fatigue?			
weather resistant?			
possible to assemble?			
prevented from unintended disassembly?			
invisible when completed?			

5 Evaluation

INSTRUCTIONS

Start by choosing the importance of each criterion, described below. The importance factors should only be chosen from the numbers below as this gives a balance in results and a possibility to compare results. Then select the statement that match the connection best, mark it with an "x", and add comments and assumptions. The grade of the criterion will automatically be calculated as the importance times the criteria point described below. The points are, as the importance, fixed values and should not be chanced. When everything is filled in, the result will appear on the result page.

IMPORTANCE	
The importance of each criterion regarding the connection can be chosen according to the scale below.	
0	Not relevant
1	Relevant
2	Extra important

CRITERIA POINTS	
All criteria are given a point, shown below, depending on the choice of statement.	
3	Desired
1	Acceptable
-1	Unacceptable

RESULT DESCRIPTION

On the result page all grades are compiled. It can be seen which criteria that are satisfactory and which that has to be considered in a redesign. Results from criteria that could be improved are marked red and good results are marked green. Also the number of handled criteria, a mean grade of the connection based only on the handled criteria, and an assembly index are shown.

RESULT

CONNECTION TITLE

NUMBER OF CRITERIA USED	0
MEAN GRADE	-
INDEX	-

SUMMARY OF CRITERIA

Criteria	Importance	Point	Grade
Stability	0	-	-
Positioning of Elements	0	-	-
Positioning of Loose Parts	0	-	-
Number of Loose Parts	0	-	-
Size of Loose Parts	0	-	-
Weight of Loose Parts	0	-	-
Need for Assembly Workers	0	-	-
Safety for Workers	0	-	-
Tools	0	-	-
Accessibility	0	-	-
Fixation Method	0	-	-
Protruding Parts	0	-	-
Multi-Purpose Connections	0	-	-
Fool Proof	0	-	-
Demountability	0	-	-
Tolerance	0	-	-

Stability	**IMPORTANCE: 0**	
Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provide stability at once		-
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		
Comments and assumptions:		

Positioning of Elements	**IMPORTANCE: 0**	
Elements should preferably be guided into their final position.		
STATEMENTS	**CHOICE**	**GRADE**
The connection guides elements into position		-
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements		
Comments and assumptions:		

Positioning of Loose Parts	IMPORTANCE: 0	
Loose connection details are preferred to be self guiding.		
STATEMENTS	**CHOICE**	**GRADE**
All loose connection details are self guiding		-
Some loose connection details are self guiding		
No loose connection details are self guiding		
Comments and assumptions:		

Number of Loose Parts	IMPORTANCE: 0	
The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.		
STATEMENTS	**CHOICE**	**GRADE**
One loose part (or no loose parts)		-
Two or three loose parts		
More than three loose parts		
Comments and assumptions:		

Size of Loose Parts	IMPORTANCE: 0	
Long or wide loose parts that are hard to handle should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The longest measurement is between 2 cm and 30 cm		-
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		
Comments and assumptions:		

Weight of Loose Parts	IMPORTANCE: 0	
Heavy loose parts should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
No parts weigh more than 1 kg		-
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		
Comments and assumptions:		

Need for Assembly Workers	IMPORTANCE: 0	
The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be assembled by one worker with no special skills		-
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		
Comments and assumptions:		

Safety for Workers	IMPORTANCE: 0	
The risk for workers getting injured in the assembly process because of the connection should be minimized.		
STATEMENTS	**CHOICE**	**GRADE**
No risk for workers getting injured		-
The risk for workers getting injured is small		
The assembly work is risky for the workers		
Comments and assumptions:		

Tools	IMPORTANCE: 0	
Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.		
STATEMENTS	**CHOICE**	**GRADE**
Not more than one small tool needed for the assembly		-
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		
Comments and assumptions:		

Accessibility	IMPORTANCE: 0	
Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be handled from one side only with easy access		-
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		
Comments and assumptions:		

Fixation Method	IMPORTANCE: 0	
Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provides fixation easily using snap fits or with help of a simple motion		-
Screws are used as fasteners or a combination of motions is needed		
Complex connections such as welding, grouting or other wet connections are used		
Comments and assumptions:		

Protruding Parts	IMPORTANCE: 0	
It is important that connections are not fragile or harmful to components, protruding parts, other connections and personnel.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is not harmful to elements or fragile in itself		-
Damage is possible but can be repaired easily		
Damage is possible which is difficult to repair or result in that whole elements have to be replaced		
Comments and assumptions:		

Multi-Purpose Connections	**IMPORTANCE:**	**0**
Try to integrate lifting devices in the connection. The elements should hang straight when lifted.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can serve as lifting device without changes		-
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device		
Comments and assumptions:		

Fool Proof	**IMPORTANCE:**	**0**
It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is hard to misassemble		-
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled		
Comments and assumptions:		

Demountability	IMPORTANCE: 0	
Elements should be possible to demount without getting damaged.		
STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself		-
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		
Comments and assumptions:		

Tolerance	IMPORTANCE: 0	
Connections that are easy to adjust regarding tolerances are preferred.		
STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		-
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted		
Comments and assumptions:		

6 Part Reduction

MINIMIZE THE NUMBER OF PARTS USING THE FOLLOWING QUESTIONS		
Answer the following questions for each part in the connection. If all questions concerning a part result in negative answers, the studied part could be eliminated or combined with another part.		
Question	**Yes**	**No**
Does the part move relative all other parts?		
Must the part be of another material than other parts?		
Must the part be separated from other parts, or else one or more of the other parts' assembly will be impossible?		

APPENDIX B

Case Study

Contents

1 Consolis Floor-to-Floor Connection

RESULT

Consolis Floor-to-Floor Connection

NUMBER OF CRITERIA USED	13
MEAN GRADE	2,33
INDEX	83%

SUMMARY OF CRITERIA

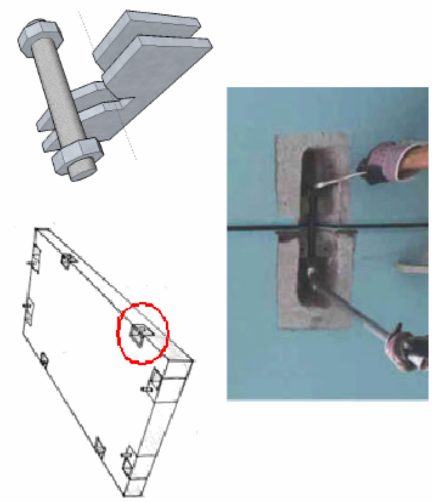
Criteria	Importance	Point	Grade
Stability	0	-	-
Positioning of Elements	0	-	-
Positioning of Loose Parts	1	3	3
Number of Loose Parts	1	3	3
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3
Need for Assembly Workers	1	3	3
Safety for Workers	1	1	1
Tools	2	1	2
Accessibility	1	3	3
Fixation Method	2	1	2
Protruding Parts	1	3	3
Multi-Purpose Connections	0	-	-
Fool Proof	1	3	3
Demountability	1	3	3
Tolerance	1	3	3

CONNECTION DESCRIPTION

Consolis Floor-to-Floor Connection

The connection is used between concrete elements in a building system developed by Consolis. The connection in the study is a floor-to-floor connection but the same connection can also be used for wall-to-wall connection, this is however not treated in the study. Each connection consists of steel plates cast into the elements where the connection is located. The connection is locked by a treaded bar and two nuts fixating these steel plates. To ease the assembly the bar and the bolts are assumed to be preassembled; delivered to the assembly site as one part. It is also assumed that this connection is not used as a point for lifting as other connections in the same element are more suitable for connecting a lifting devise.

PICTURE



Stability — IMPORTANCE: 0

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		-
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The element is stable with no help from the studied connection.*

Positioning of Loose Parts — IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding	x	3
Some loose connection details are self guiding		
No loose connection details are self guiding		

Comments and assumptions: *The threaded bar with nuts used to fix the connection can easily be placed in the connection thanks to the triangularly shaped notch in the steel plates.*

Positioning of Elements — IMPORTANCE: 0

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements		

Comments and assumptions: *The element is assumed to be positioned by other connections.*

Number of Loose Parts — IMPORTANCE: 1

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)	x	3
Two or three loose parts		
More than three loose parts		

Comments and assumptions: *The loose parts of the connection are assumed to consist of a threaded bar with nuts which are preassembled into one piece.*

Size of Loose Parts

IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 1

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	3
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *It is assumed that one worker can manage to fixate the connection.*

Weight of Loose Parts

IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg	x	3
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *There are no imminent risk for workers getting hurt when inserting and fastening the nuts to the threaded bar. The workers could however get pinched.*

Tools		IMPORTANCE: 2
Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.		
STATEMENTS	**CHOICE**	**GRADE**
Not more than one small tool needed for the assembly		2
Two or three small tools are needed	x	
Many different small tools or heavy, large or cumbersome tools are needed		
Comments and assumptions: *Two wrenches are needed to fix the connection.*		

Fixation Method		IMPORTANCE: 2
Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provides fixation easily using snap fits or with help of a simple motion		2
Screws are used as fasteners or a combination of motions is needed	x	
Complex connections such as welding, grouting or other wet connections are used		
Comments and assumptions:		

Accessibility		IMPORTANCE: 1
Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be handled from one side only with easy access	x	3
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		
Comments and assumptions:		

Protruding Parts		IMPORTANCE: 1
Connections should not be harmful to itself, components, protruding parts, other connections or personnel.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is not harmful	x	3
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		
Comments and assumptions: *There are no protruding parts.*		

Multi-Purpose Connections

IMPORTANCE: 0

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device		

Comments and assumptions: *It is assumed that other connections are used for lifting.*

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself	x	3
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		

Comments and assumptions:

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble	x	3
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled		

Comments and assumptions: *It is assumed that a torque meter is used to secure that the nuts are fixed properly.*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled	x	3
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions: *The tolerance is absorbed as the holes in the steel plates are larger than the threaded rod, therefore no adjustment is needed.*

2 Consolis Wall-to-Floor Connection

RESULT

Consolis Wall-to-Floor Connection

NUMBER OF CRITERIA USED	16
MEAN GRADE	1,45
INDEX	61%

SUMMARY OF CRITERIA

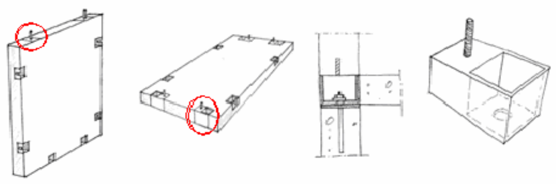
Criteria	Importance	Point	Grade
Stability	1	3	3
Positioning of Elements	2	-1	-2
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	2	1	2
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3
Need for Assembly Workers	2	3	6
Safety for Workers	1	1	1
Tools	2	3	6
Accessibility	1	3	3
Fixation Method	2	1	2
Protruding Parts	2	-1	-2
Multi-Purpose Connections	1	1	1
Fool Proof	1	1	1
Demountability	1	3	3
Tolerance	1	3	3

CONNECTION DESCRIPTION

Consolis Wall-to-Floor Connection

This connection in the figure comes from a system developed by Consolis. It is designed to connect wall elements to floor elements. The connection consists of a steel box that is cast into concrete elements in a factory. A bolt from one of the steel boxes in an element underneath is fixed with a nut in the steel box in the element above. The same connection is used both when a wall element is placed on top of a floor element and when a floor element is placed on top of a wall element. However, the study only handles the second of these cases. This connection is assumed to serve as a lifting point if a bolt is placed on the rod.

PICTURE



Stability

IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once	x	3
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The element will be stable as soon it is put in its position.*

Positioning of Loose Parts

IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-1
Some loose connection details are self guiding		
No loose connection details are self guiding	x	

Comments and assumptions: *Nuts are not guided into position when assembled.*

Positioning of Elements

IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-2
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions:

Number of Loose Parts

IMPORTANCE: 2

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)		2
Two or three loose parts	x	
More than three loose parts		

Comments and assumptions: *One nut and one washer are assumed to be used.*

Size of Loose Parts

IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	6
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *It is assumed that one worker can manage to fixate the connection.*

Weight of Loose Parts

IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg	x	3
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *There are no imminent risk for workers getting hurt when fastening the nuts to the threaded bar. The workers could however get pinched.*

Tools		IMPORTANCE: 2
Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.		
STATEMENTS	**CHOICE**	**GRADE**
Not more than one small tool needed for the assembly	x	6
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		
Comments and assumptions: *One wrench is assumed to be needed to fix the connection.*		

Fixation Method		IMPORTANCE: 2
Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provides fixation easily using snap fits or with help of a simple motion		2
Screws are used as fasteners or a combination of motions is needed	x	
Complex connections such as welding, grouting or other wet connections are used		
Comments and assumptions:		

Accessibility		IMPORTANCE: 1
Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be handled from one side only with easy access	x	3
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		
Comments and assumptions:		

Protruding Parts		IMPORTANCE: 2
Connections should not be harmful to itself, components, protruding parts, other connections or personnel.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is not harmful		-2
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced	x	
Comments and assumptions: *The treaded rod can be damaged itself and damage other elements.*		

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		
The connection can serve as lifting device with of some extra equipment	x	1
The connection does not serve as lifting device		

Comments and assumptions: *It is assumed that a lifting device can be attached to the connection.*

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself	x	
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		3
The connection provides no disassemblabillity		

Comments and assumptions:

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble		
The connection can be misassembled but guiding features are provided in order to prevent misassembly	x	1
The connection can easily be misassembled		

Comments and assumptions: *A torque meter is assumed to be used.*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled	x	
The connection is easy to adjust for size variations		3
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions: *The tolerance is absorbed as the hole in the steel box is larger than the threaded rod, therefore no adjustment is needed.*

3 Concrete Beam-Column Connection

RESULT

Concrete Beam-Column Connection

NUMBER OF CRITERIA USED	16
MEAN GRADE	1,45
INDEX	61%

SUMMARY OF CRITERIA

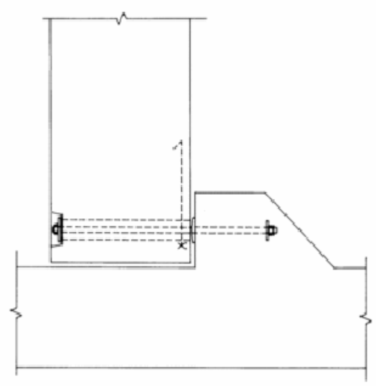
Criteria	Importance	Point	Grade
Stability	1	3	3
Positioning of Elements	2	-1	-2
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	2	1	2
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3
Need for Assembly Workers	2	3	6
Safety for Workers	1	1	1
Tools	2	3	6
Accessibility	1	3	3
Fixation Method	2	1	2
Protruding Parts	2	-1	-2
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	3	3
Demountability	1	3	3
Tolerance	1	3	3

CONNECTION DESCRIPTION

Concrete Beam-Column Connection

This beam-to-column connection is used for prefabricated concrete elements. The beam is slipped on to a treaded rod that is precast into the column. On the topside of the beam the connection is fixed with a nut. The hole in the beam is assumed not to be filled with concrete which is a possibility.

PICTURE



Stability

IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once	x	3
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The connection is assumed to be stable as soon the beam is placed on the corbel.*

Positioning of Loose Parts

IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-1
Some loose connection details are self guiding		
No loose connection details are self guiding	x	

Comments and assumptions: *Nuts cannot be judged as self guiding.*

Positioning of Elements

IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-2
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions: *The hole is assumed to be a little larger than the steel rod. This is however not enough to be judged as self guiding.*

Number of Loose Parts

IMPORTANCE: 2

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)		2
Two or three loose parts	x	
More than three loose parts		

Comments and assumptions: *One nut and one washer are assumed to be used.*

Size of Loose Parts — IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers — IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	6
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *The fixation work can be performed by one worker in addition to the crane operator.*

Weight of Loose Parts — IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg	x	3
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers — IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *The workers could get pinched during positioning.*

Tools — IMPORTANCE: 2

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly	x	6
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions: *The nut is assumed to be fastened using a wrench or a similar tool.*

Fixation Method — IMPORTANCE: 2

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion		
Screws are used as fasteners or a combination of motions is needed	x	2
Complex connections such as welding, grouting or other wet connections are used		

Comments and assumptions:

Accessibility — IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access	x	3
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		

Comments and assumptions:

Protruding Parts — IMPORTANCE: 2

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful		
Damage is possible but can be repaired easily		-2
Damage is possible but is difficult to repair or result in that whole elements have to be replaced	x	

Comments and assumptions: *If the extruding rod gets damaged it might be hard to repair.*

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions: *The element has to be lifted in place and it would be preferred if the connection could be used.*

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself	x	3
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		

Comments and assumptions:

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble	x	3
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled		

Comments and assumptions: *It is assumed that a torque meter is used to secure that the nut is fixed properly.*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled	x	3
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions: *The hole is assumed to be larger than the treaded bar.*

4 Steel Beam-to-Column Connection

RESULT

Steel Beam-to-Column Connection

NUMBER OF CRITERIA USED	16
MEAN GRADE	1,09
INDEX	52%

SUMMARY OF CRITERIA

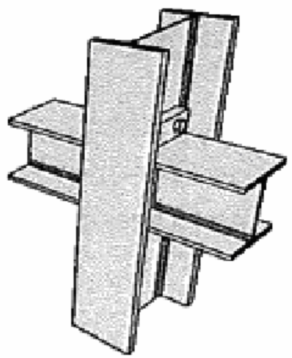
Criteria	Importance	Point	Grade
Stability	1	1	1
Positioning of Elements	2	-1	-2
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	2	-1	-2
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3
Need for Assembly Workers	2	3	6
Safety for Workers	1	1	1
Tools	2	1	2
Accessibility	1	1	1
Fixation Method	2	1	2
Protruding Parts	2	3	6
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	1	1
Demountability	1	3	3
Tolerance	1	1	1

CONNECTION DESCRIPTION

Steel Beam-to-Column Connection

The connection consists of standard hot-rolled steel beams fixed together with nuts and bolts. The connection is adopted from SBI (1988). A steel plate with predrilled holes is welded in a factory to the end of the horizontal beams. Also the vertical beam have predrilled holes were the horizontal beam is to be fastened.

PICTURE



Stability

IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		1
Stable after a small fixation or adjustment of the connection	x	
Major fixation operations or temporary supports are needed		

Comments and assumptions: *It is assumed that the beam will be stabile when two of the screws are fastened.*

Positioning of Loose Parts

IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-1
Some loose connection details are self guiding		
No loose connection details are self guiding	x	

Comments and assumptions:

Positioning of Elements

IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-2
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions: *The beam has to be lifted into its correct position.*

Number of Loose Parts

IMPORTANCE: 2

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)		-2
Two or three loose parts		
More than three loose parts	x	

Comments and assumptions:

Size of Loose Parts

IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	6
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions:

Weight of Loose Parts

IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg	x	3
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *There is a risk that the worker will get pinched.*

Tools

IMPORTANCE: 2

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly		
Two or three small tools are needed	x	2
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions: *It is assumed that two wrenches are needed.*

Fixation Method

IMPORTANCE: 2

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion		
Screws are used as fasteners or a combination of motions is needed	x	2
Complex connections such as welding, grouting or other wet connections are used		

Comments and assumptions:

Accessibility

IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access		
The connection must be handled from two sides, but is easy to access	x	1
Restricted access or more than two sides needed for handling		

Comments and assumptions: *The bolts have to be accesses from two sides.*

Protruding Parts

IMPORTANCE: 2

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful	x	6
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		

Comments and assumptions: *No protruding parts.*

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions:

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself	x	3
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		

Comments and assumptions:

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble		1
The connection can be misassembled but guiding features are provided in order to prevent misassembly	x	
The connection can easily be misassembled		

Comments and assumptions: *It is assumed that a torque meter is used to secure that the nut is fixed properly.*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		1
The connection is easy to adjust for size variations	x	
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions:

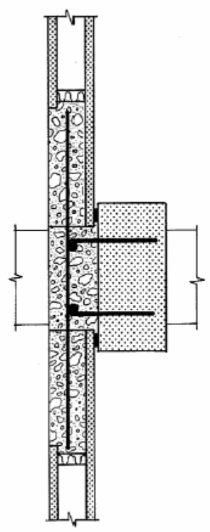
5 Concrete Cast in-situ Connection

CONNECTION DESCRIPTION

Concrete Cast in-situ Connection

This connection is a joint between prefabricated concrete plates and a prefabricated concrete wall or beam. Extra reinforcement bars are added and concrete is cast in situ in order to make the connection fixed. No extra supports are assumed to be needed before the concrete is cast.

PICTURE



RESULT

Concrete Cast in-situ Connection

NUMBER OF CRITERIA USED	15
MEAN GRADE	-0,37
INDEX	16%

SUMMARY OF CRITERIA

Criteria	Importance	Point	Grade
Stability	1	3	3
Positioning of Elements	1	-1	-1
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	1	-1	-1
Size of Loose Parts	1	-1	-1
Weight of Loose Parts	1	1	1
Need for Assembly Workers	2	-1	-2
Safety for Workers	1	-1	-1
Tools	2	-1	-2
Accessibility	1	-1	-1
Fixation Method	2	-1	-2
Protruding Parts	2	1	2
Multi-Purpose Connections	0	-	-
Fool Proof	1	-1	-1
Demountability	1	-1	-1
Tolerance	1	1	1

Stability — IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once	x	3
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The concrete plates are assumed to be stable even before the concrete in the joint is cast.*

Positioning of Loose Parts — IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-1
Some loose connection details are self guiding		
No loose connection details are self guiding	x	

Comments and assumptions: *Loose reinforcement bars are assumed to be needed.*

Positioning of Elements — IMPORTANCE: 1

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-1
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions:

Number of Loose Parts — IMPORTANCE: 1

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)		-1
Two or three loose parts		
More than three loose parts	x	

Comments and assumptions:

Size of Loose Parts — IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm		-1
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm	x	

Comments and assumptions: *The reinforcement bars in the joint are assumed to be over 50 cm long.*

Need for Assembly Workers — IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills		-2
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills	x	

Comments and assumptions: *To cast concrete special skills are needed.*

Weight of Loose Parts — IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg		1
Some parts weigh between 1 kg and 3 kg	x	
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers — IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		-1
The risk for workers getting injured is small		
The assembly work is risky for the workers	x	

Comments and assumptions: *Workers can get hurt by reinforcement bars or get exposed to fresh concrete during casting.*

Tools

IMPORTANCE: 2

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly		-2
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed	x	

Comments and assumptions: *Different tools are needed to bind the reinforcement bars and to cast the concrete.*

Fixation Method

IMPORTANCE: 2

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion		-2
Screws are used as fasteners or a combination of motions is needed		
Complex connections such as welding, grouting or other wet connections are used	x	

Comments and assumptions:

Accessibility

IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access		-1
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling	x	

Comments and assumptions: *It can be difficult to place reinforcement bars into the connection.*

Protruding Parts

IMPORTANCE: 2

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful		2
Damage is possible but can be repaired easily	x	
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		

Comments and assumptions: *The reinforcement bars in the plates can be damaged. This can however be repaired before casting.*

Multi-Purpose Connections

IMPORTANCE: 0

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device		

Comments and assumptions:

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself		-1
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity	x	

Comments and assumptions:

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble		-1
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled	x	

Comments and assumptions: *It it easy to mound the reinforcement incorrectly*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		1
The connection is easy to adjust for size variations	x	
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions:

6 Beam with Movable Steel Plate

RESULT

Beam with Movable Steel Plate

NUMBER OF CRITERIA USED	13
MEAN GRADE	2,47
INDEX	87%

SUMMARY OF CRITERIA

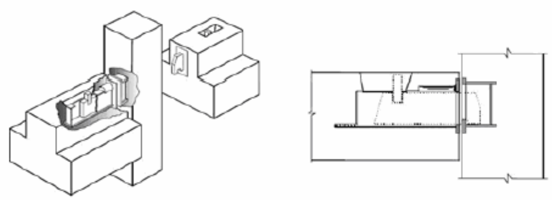
Criteria	Importance	Point	Grade
Stability	1	1	1
Positioning of Elements	2	1	2
Positioning of Loose Parts	0	-	-
Number of Loose Parts	2	3	6
Size of Loose Parts	0	-	-
Weight of Loose Parts	0	-	-
Need for Assembly Workers	2	3	6
Safety for Workers	1	3	3
Tools	2	3	6
Accessibility	1	3	3
Fixation Method	2	3	6
Protruding Parts	2	3	6
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	3	3
Demountability	1	3	3
Tolerance	1	3	3

CONNECTION DESCRIPTION

Beam with Movable Steel Plate

The connection consists of a beam hooked to a column with help of a movable steel plate. The connection is assumed to be made of steel cast into concrete elements. It is supposed that the hook is easy to slide horizontally without any need for tools. The purpose with the movable hook is the possibility to lift the beam in place before sliding out the hook into the column which decreases the risk of jamming and damage of the connection detail.

PICTURE



Stability — IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		1
Stable after a small fixation or adjustment of the connection	x	
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The movable steel plate must be adjusted into place before its stable.*

Positioning of Loose Parts — IMPORTANCE: 0

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-
Some loose connection details are self guiding		
No loose connection details are self guiding		

Comments and assumptions:

Positioning of Elements — IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		2
The connection partly guides elements into position, e.g. self guiding in one direction	x	
The connection provides no self guiding for elements		

Comments and assumptions: *The movable steel plate is guided into place after the beam is in right position in front of the column.*

Number of Loose Parts — IMPORTANCE: 2

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)	x	6
Two or three loose parts		
More than three loose parts		

Comments and assumptions:

Size of Loose Parts — IMPORTANCE: 0

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm		-
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers — IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	6
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *The movable steel plate can be moved by one worker.*

Weight of Loose Parts — IMPORTANCE: 0

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg		-
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers — IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured	x	3
The risk for workers getting injured is small		
The assembly work is risky for the workers		

Comments and assumptions: *No risk for jamming fingers in the movable steel plate.*

Tools

IMPORTANCE: 2

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly	x	6
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions:

Fixation Method

IMPORTANCE: 2

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion	x	6
Screws are used as fasteners or a combination of motions is needed		
Complex connections such as welding, grouting or other wet connections are used		

Comments and assumptions: *Only the movable steel plate needs to be moved into place.*

Accessibility

IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access	x	3
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		

Comments and assumptions:

Protruding Parts

IMPORTANCE: 2

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful	x	6
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		

Comments and assumptions: *No protruding parts that can damage other elements or be damage itself.*

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions:

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself	x	3
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		

Comments and assumptions: *The connection can be demounted in the same way it is mounted.*

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble	x	3
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled		

Comments and assumptions:

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled	x	3
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions: *The tolerances adjust automatically with help of the movable steel plate.*

Beam with Movable Steel Plate

7 Welded Connection of Steel Beams

RESULT

Welded Connection of Steel Beams

NUMBER OF CRITERIA USED	13
MEAN GRADE	-0,26
INDEX	18%

SUMMARY OF CRITERIA

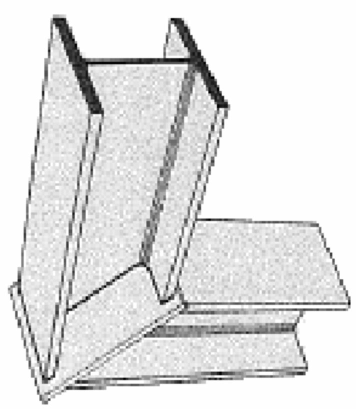
Criteria	Importance	Point	Grade
Stability	1	-1	-1
Positioning of Elements	2	-1	-2
Positioning of Loose Parts	0	-	-
Number of Loose Parts	2	3	6
Size of Loose Parts	0	-	-
Weight of Loose Parts	0	-	-
Need for Assembly Workers	2	-1	-2
Safety for Workers	1	-1	-1
Tools	2	-1	-2
Accessibility	1	-1	-1
Fixation Method	2	-1	-2
Protruding Parts	2	1	2
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	-1	-1
Demountability	1	-1	-1
Tolerance	1	1	1

CONNECTION DESCRIPTION

Welded Connection of Steel Beams

A welded connection of two hot-rolled steel beams is shown in the figure. The plate between the beam ends is assumed to be welded to one of the beams in a factory and only needs to be welded to the other beam on site. Welding require workers with special skills. With rightfully preformed welds, the connection will be very stiff. The assembly of the connection is however weather sensitive; rain and wind can be harmful.

PICTURE



Stability — IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		-1
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed	x	

Comments and assumptions: *The connection is not stable before welding is performed.*

Positioning of Loose Parts — IMPORTANCE: 0

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-
Some loose connection details are self guiding		
No loose connection details are self guiding		

Comments and assumptions:

Positioning of Elements — IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-2
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions: *The beams are not fixed before welding.*

Number of Loose Parts — IMPORTANCE: 2

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)	x	6
Two or three loose parts		
More than three loose parts		

Comments and assumptions:

Size of Loose Parts

IMPORTANCE: 0

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm		-
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills		-2
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills	x	

Comments and assumptions:

Weight of Loose Parts

IMPORTANCE: 0

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg		-
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		-1
The risk for workers getting injured is small		
The assembly work is risky for the workers	x	

Comments and assumptions: *Welding is dangerous to the workers.*

Tools	IMPORTANCE: 2	
Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.		
STATEMENTS	**CHOICE**	**GRADE**
Not more than one small tool needed for the assembly		-2
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed	x	
Comments and assumptions: *Welding results in a need for large and heavy equipment.*		

Fixation Method	IMPORTANCE: 2	
Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provides fixation easily using snap fits or with help of a simple motion		-2
Screws are used as fasteners or a combination of motions is needed		
Complex connections such as welding, grouting or other wet connections are used	x	
Comments and assumptions:		

Accessibility	IMPORTANCE: 1	
Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be handled from one side only with easy access		-1
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling	x	
Comments and assumptions: *The connection weld is performed around the whole beam.*		

Protruding Parts	IMPORTANCE: 2	
Connections should not be harmful to itself, components, protruding parts, other connections or personnel.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is not harmful		2
Damage is possible but can be repaired easily	x	
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		
Comments and assumptions: *The connection is located along the edge of the beam. It is considered to be sharp and therefore harmful to other elements.*		

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions:

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself		-1
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity	x	

Comments and assumptions:

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble		-1
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled	x	

Comments and assumptions: *The weld can be performed in an incorrect way.*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		1
The connection is easy to adjust for size variations	x	
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions: *The tolerances are taken by the weld.*

8 Timber Connection with Dowels

RESULT

Timber Connection with Dowels

NUMBER OF CRITERIA USED	16
MEAN GRADE	1,13
INDEX	53%

SUMMARY OF CRITERIA

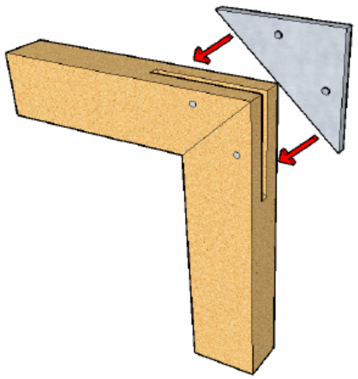
Criteria	Importance	Point	Grade
Stability	1	-1	-1
Positioning of Elements	1	-1	-1
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	1	1	1
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3
Need for Assembly Workers	1	3	3
Safety for Workers	1	3	3
Tools	1	3	3
Accessibility	1	1	1
Fixation Method	1	1	1
Protruding Parts	1	3	3
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	1	1
Demountability	1	1	1
Tolerance	1	-1	-1

CONNECTION DESCRIPTION

Timber Connection with Dowels

This timber connection consists of two timber members joined together with steel dowels. There is also a plate inserted in the connection through which the dowels are placed. The plate increases the stiffness of the connection which can be a problem in wood connections.

PICTURE



Stability

IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		-1
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed	x	

Comments and assumptions: *Many operations have to be performed before the connection is stable.*

Positioning of Loose Parts

IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-1
Some loose connection details are self guiding		
No loose connection details are self guiding	x	

Comments and assumptions: *The plate is assumed to have sharp edges.*

Positioning of Elements

IMPORTANCE: 1

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-1
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions: *The element is assumed to be placed close to each other with no self guiding.*

Number of Loose Parts

IMPORTANCE: 1

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)		1
Two or three loose parts	x	
More than three loose parts		

Comments and assumptions:

Size of Loose Parts

IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 1

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	3
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *Only a siple motion.*

Weight of Loose Parts

IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg	x	3
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured	x	3
The risk for workers getting injured is small		
The assembly work is risky for the workers		

Comments and assumptions:

Tools

IMPORTANCE: 1

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly	x	3
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions: *Only a hammer is assumed to be needed.*

Fixation Method

IMPORTANCE: 1

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion		1
Screws are used as fasteners or a combination of motions is needed	x	
Complex connections such as welding, grouting or other wet connections are used		

Comments and assumptions: *Combined motion is needed; insertion of the plate and insertion of the dowels.*

Accessibility

IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access		1
The connection must be handled from two sides, but is easy to access	x	
Restricted access or more than two sides needed for handling		

Comments and assumptions: *The plate and the dowels are inserted from different sides.*

Protruding Parts

IMPORTANCE: 1

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful	x	3
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		

Comments and assumptions:

Multi-Purpose Connections IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions:

Demountability IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself		1
Disassembly is possible without causing damage to elements, but the connection itself can be damaged	x	
The connection provides no disassemblabillity		

Comments and assumptions: *The dowels can be removed with melp of some tools.*

Fool Proof IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble		1
The connection can be misassembled but guiding features are provided in order to prevent misassembly	x	
The connection can easily be misassembled		

Comments and assumptions: *The plate can be mounted incorrectly.*

Tolerance IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		-1
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted	x	

Comments and assumptions:

9 Roller Bearing for Volume Elements

RESULT

Roller Bearing for Volume Elements

NUMBER OF CRITERIA USED	16
MEAN GRADE	2,53
INDEX	88%

SUMMARY OF CRITERIA

Criteria	Importance	Point	Grade
Stability	1	3	3
Positioning of Elements	2	3	6
Positioning of Loose Parts	1	3	3
Number of Loose Parts	1	3	3
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	1	1
Need for Assembly Workers	1	3	3
Safety for Workers	1	1	1
Tools	1	3	3
Accessibility	1	3	3
Fixation Method	1	3	3
Protruding Parts	1	3	3
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	3	3
Demountability	1	3	3
Tolerance	1	3	3

CONNECTION DESCRIPTION

Roller Bearing for Volume Elements

This connection is used between volume elements. It consists of three parts where the cylinder is loose while the two other details are attached to the elements in a factory. At the assembly site the cylinder is placed on the lower element just before the next element is put in place. The connection cannot resist tension in the vertical direction but it is assumed to be stable thanks to the self weight of the elements above. If not, the tensile forces have to be resisted in another way.

PICTURE

Stability

IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once	x	3
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The element is instant placed in its final position.*

Positioning of Loose Parts

IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding	x	3
Some loose connection details are self guiding		
No loose connection details are self guiding		

Comments and assumptions: *The connection is rounded were the loose part is placed.*

Positioning of Elements

IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position	x	6
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements		

Comments and assumptions: *The roller bearing provides self guiding.*

Number of Loose Parts

IMPORTANCE: 1

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)	x	3
Two or three loose parts		
More than three loose parts		

Comments and assumptions:

Size of Loose Parts

IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions: *The roller bearing is assumed to be less than 30 cm long.*

Need for Assembly Workers

IMPORTANCE: 1

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	3
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *Only to put the roller in place.*

Weight of Loose Parts

IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg		1
Some parts weigh between 1 kg and 3 kg	x	
Some parts weigh more than 3 kg		

Comments and assumptions: *The loose part is a solid metal roller and is assumed to weight between one and three kg.*

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *It is possible to drop the cylinder on the toes or jam their fingers.*

Tools		IMPORTANCE: 1
Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.		
STATEMENTS	**CHOICE**	**GRADE**
Not more than one small tool needed for the assembly	x	3
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		
Comments and assumptions:		

Fixation Method		IMPORTANCE: 1
Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provides fixation easily using snap fits or with help of a simple motion	x	3
Screws are used as fasteners or a combination of motions is needed		
Complex connections such as welding, grouting or other wet connections are used		
Comments and assumptions: *Only to lay the roller into position.*		

Accessibility		IMPORTANCE: 1
Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be handled from one side only with easy access	x	3
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		
Comments and assumptions:		

Protruding Parts		IMPORTANCE: 1
Connections should not be harmful to itself, components, protruding parts, other connections or personnel.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is not harmful	x	3
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		
Comments and assumptions: *The parts of the connection attached to the elements are assumed not to be harmful to other elements during assembly.*		

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions: *The connection on top of the volume element would be preferred to be used as a lifting point.*

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself	x	3
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		

Comments and assumptions: *The connection is assumed to be stable only by the weight of the element and will therefore be easy to demount in the same way as the assembly.*

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble	x	3
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled		

Comments and assumptions:

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled	x	3
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions: *The rollers are assumed to adjust automatically.*

10 Connection for Storage Rack

RESULT

Connection for Storage Rack

NUMBER OF CRITERIA USED	13
MEAN GRADE	1,77
INDEX	69%

SUMMARY OF CRITERIA

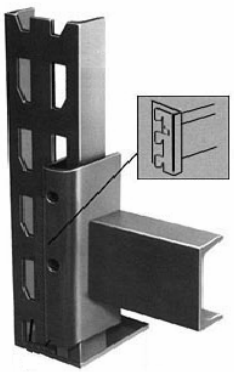
Criteria	Importance	Point	Grade
Stability	1	1	1
Positioning of Elements	1	1	1
Positioning of Loose Parts	0	-	-
Number of Loose Parts	1	3	3
Size of Loose Parts	0	-	-
Weight of Loose Parts	0	-	-
Need for Assembly Workers	1	3	3
Safety for Workers	1	1	1
Tools	1	3	3
Accessibility	1	3	3
Fixation Method	1	1	1
Protruding Parts	1	3	3
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	1	1
Demountability	1	3	3
Tolerance	1	1	1

CONNECTION DESCRIPTION

Connection for Storage Rack

Below a storage rack is shown. The connection studied is where the beam is attached to the column shown in the figure. There are holes in the column into which the beam can be hooked on to. The only tool assumed to be used is a hammer.

PICTURE



Stability — IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		
Stable after a small fixation or adjustment of the connection	x	1
Major fixation operations or temporary supports are needed		

Comments and assumptions: *The connection needs to be forced into position before stability.*

Positioning of Loose Parts — IMPORTANCE: 0

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		
Some loose connection details are self guiding		-
No loose connection details are self guiding		

Comments and assumptions:

Positioning of Elements — IMPORTANCE: 1

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		
The connection partly guides elements into position, e.g. self guiding in one direction	x	1
The connection provides no self guiding for elements		

Comments and assumptions: *When the element is put in there first position it will guide the element to its final position.*

Number of Loose Parts — IMPORTANCE: 1

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)	x	
Two or three loose parts		3
More than three loose parts		

Comments and assumptions: *No loose parts needed.*

Size of Loose Parts

IMPORTANCE: 0

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm		-
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 1

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	3
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions:

Weight of Loose Parts

IMPORTANCE: 0

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg		-
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *The assembly worker can jam their fingers in the connection as the connection can jam during assembly*

Tools

IMPORTANCE: 1

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly	x	3
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions: *Only a hammer is assumed to be used.*

Fixation Method

IMPORTANCE: 1

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion		1
Screws are used as fasteners or a combination of motions is needed	x	
Complex connections such as welding, grouting or other wet connections are used		

Comments and assumptions: *It might be neccesary to force the beam into place by a hammer from two directions.*

Accessibility

IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access	x	3
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		

Comments and assumptions:

Protruding Parts

IMPORTANCE: 1

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful	x	3
Damage is possible but can be repaired easily		
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		

Comments and assumptions: *The connection is assumed to not be harmful; no sharp edges that can injure other elements or assembly workers.*

Multi-Purpose Connections	IMPORTANCE: 1	
Try to integrate lifting devices in the connection. The elements should hang straight when lifted.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	
Comments and assumptions: *The beam is used as lifting point.*		

Demountability	IMPORTANCE: 1	
Elements should be possible to demount without getting damaged.		
STATEMENTS	**CHOICE**	**GRADE**
Disassembly is possible without causing damage to elements or the connection itself	x	3
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		
Comments and assumptions: *The connection can be demounted in the same way as the assembly.*		

Fool Proof	IMPORTANCE: 1	
It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is hard to misassemble		1
The connection can be misassembled but guiding features are provided in order to prevent misassembly	x	
The connection can easily be misassembled		
Comments and assumptions: *The connection might be fastened skew.*		

Tolerance	IMPORTANCE: 1	
Connections that are easy to adjust regarding tolerances are preferred.		
STATEMENTS	**CHOICE**	**GRADE**
The connection adjusts automatically when assembled		1
The connection is easy to adjust for size variations	x	
The connection is hard to adjust or require extra assembly time when adjusted		
Comments and assumptions: *Thus the small tolerance of the connection adjusts automatically.*		

11 Beam Shoe

RESULT

Beam Shoe

NUMBER OF CRITERIA USED	16
MEAN GRADE	1,09
INDEX	52%

SUMMARY OF CRITERIA

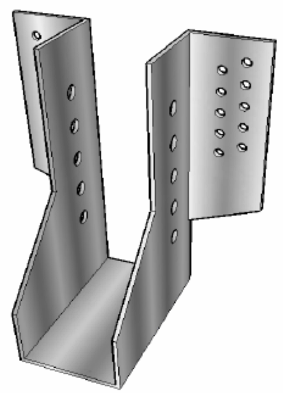
Criteria	Importance	Point	Grade
Stability	1	3	3
Positioning of Elements	2	-1	-2
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	2	-1	-2
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3
Need for Assembly Workers	2	3	6
Safety for Workers	1	1	1
Tools	2	3	6
Accessibility	1	1	1
Fixation Method	2	1	2
Protruding Parts	2	1	2
Multi-Purpose Connections	1	-1	-1
Fool Proof	1	1	1
Demountability	1	1	1
Tolerance	1	1	1

CONNECTION DESCRIPTION

Beam Shoe

The connection detail is used when fastening a timber beam to a wall or a column. It consists of a bent steel plate fixed using nails. It is assumed that the beam shoe is already fastened to the wall or column before the timber beam is lifted in place.

PICTURE



Stability

IMPORTANCE: 1

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once	x	3
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions: *No nails need to be fastened before stability.*

Positioning of Loose Parts

IMPORTANCE: 1

Loose connection details are preferred to be self guiding.

STATEMENTS	CHOICE	GRADE
All loose connection details are self guiding		-1
Some loose connection details are self guiding		
No loose connection details are self guiding	x	

Comments and assumptions: *The nails are not self guided.*

Positioning of Elements

IMPORTANCE: 2

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-2
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements	x	

Comments and assumptions: *The beam shoe has sharp edges.*

Number of Loose Parts

IMPORTANCE: 2

The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.

STATEMENTS	CHOICE	GRADE
One loose part (or no loose parts)		-2
Two or three loose parts		
More than three loose parts	x	

Comments and assumptions: *Many nails are used.*

Size of Loose Parts

IMPORTANCE: 1

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm	x	3
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Need for Assembly Workers

IMPORTANCE: 2

The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.

STATEMENTS	CHOICE	GRADE
The connection can be assembled by one worker with no special skills	x	6
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		

Comments and assumptions: *Handling nail and hammer are not considered as special skills.*

Weight of Loose Parts

IMPORTANCE: 1

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg	x	3
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Safety for Workers

IMPORTANCE: 1

The risk for workers getting injured in the assembly process because of the connection should be minimized.

STATEMENTS	CHOICE	GRADE
No risk for workers getting injured		1
The risk for workers getting injured is small	x	
The assembly work is risky for the workers		

Comments and assumptions: *Workers can get injured while fixating nails.*

Beam Shoe

Tools

IMPORTANCE: 2

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly	x	6
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions: *Only a hammer is used.*

Fixation Method

IMPORTANCE: 2

Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.

STATEMENTS	CHOICE	GRADE
The connection provides fixation easily using snap fits or with help of a simple motion		2
Screws are used as fasteners or a combination of motions is needed	x	
Complex connections such as welding, grouting or other wet connections are used		

Comments and assumptions:

Accessibility

IMPORTANCE: 1

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access		1
The connection must be handled from two sides, but is easy to access	x	
Restricted access or more than two sides needed for handling		

Comments and assumptions: *Nails must be fastened from two sides.*

Protruding Parts

IMPORTANCE: 2

Connections should not be harmful to itself, components, protruding parts, other connections or personnel.

STATEMENTS	CHOICE	GRADE
The connection is not harmful		2
Damage is possible but can be repaired easily	x	
Damage is possible but is difficult to repair or result in that whole elements have to be replaced		

Comments and assumptions: *The beam shoe can damage other elements.*

Multi-Purpose Connections

IMPORTANCE: 1

Try to integrate lifting devices in the connection. The elements should hang straight when lifted.

STATEMENTS	CHOICE	GRADE
The connection can serve as lifting device without changes		-1
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device	x	

Comments and assumptions:

Demountability

IMPORTANCE: 1

Elements should be possible to demount without getting damaged.

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself		1
Disassembly is possible without causing damage to elements, but the connection itself can be damaged	x	
The connection provides no disassemblability		

Comments and assumptions: *The holes from the nails are not considered to be crucial.*

Fool Proof

IMPORTANCE: 1

It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.

STATEMENTS	CHOICE	GRADE
The connection is hard to misassemble		1
The connection can be misassembled but guiding features are provided in order to prevent misassembly	x	
The connection can easily be misassembled		

Comments and assumptions: *Some of the nails might be forgotten.*

Tolerance

IMPORTANCE: 1

Connections that are easy to adjust regarding tolerances are preferred.

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		1
The connection is easy to adjust for size variations	x	
The connection is hard to adjust or require extra assembly time when adjusted		

Comments and assumptions:

Beam Shoe

12 Summation of Results

RESULT FROM CASE STUDY	Consolis Floor-to-Floor Connection	Consolis Wall-to-Floor Connection	Concrete Beam-Column Connection	Steel Beam-to-Column Connection	Concrete Cast in-situ Connection	Beam with Movable Steel Plate	Welded Connection of Steel Beams	Timber Connection with Dowels	Roller Bearing for Volume Elements	Connection for Storage Rack	Beam Shoe
Number of Criteria Used	13	16	16	16	15	13	13	16	16	13	16
Mean Grade	2,33	1,45	1,45	1,09	-0,37	2,47	-0,26	1,13	2,53	1,77	1,09
Index	83%	61%	61%	52%	16%	87%	18%	53%	88%	69%	52%
Stability	-	3	3	1	3	1	-1	-1	3	1	3
Positioning of Elements	-	-2	-2	-2	-1	2	-2	-1	6	1	-2
Positioning of Loose Parts	3	-1	-1	-1	-1	-	-	-1	3	-	-1
Number of Loose Parts	3	2	2	-2	-1	6	6	1	3	3	-2
Size of Loose Parts	3	3	3	3	-1	-	-	3	3	-	3
Weight of Loose Parts	3	3	3	3	1	-	-	3	1	-	3
Need for Assembly Workers	3	6	6	6	-2	6	-2	3	3	3	6
Safety for Workers	1	1	1	1	-1	3	-1	3	1	1	1
Tools	2	6	6	2	-2	6	-2	3	3	3	6
Accessibility	3	3	3	1	-1	3	-1	1	3	3	1
Fixation Method	2	2	2	2	-2	6	-2	1	3	1	2
Protruding Parts	3	-2	-2	6	2	6	2	3	3	3	2
Multi-Purpose Connections	-	1	-1	-1	-	-1	-1	-1	-1	-1	-1
Fool Proof	3	1	3	1	-1	3	-1	1	3	1	1
Demountability	3	3	3	3	-1	3	-1	1	3	3	1
Tolerance	3	3	3	1	1	3	1	-1	3	1	1