STRUCTURAL ANALYSIS AND DESIGN OF FASTENERS ON STEEL FOR SOFTWARE IMPLEMENTATION

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To my family

In a society that profits from your self-doubt, liking yourself is a rebellious act

Caroline Caldwell

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Firstly, I would like to thank my family. All these years, in three different universities, demanded a lot of patience and encouragement from them. I would not be able to do it alone, and my past achievements, likewise the future ones, are specially dedicated to them.

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ABSTRACT

Steel structures are widely used in the construction field, especially due to their high durability and load capacity. To support their analysis and design, software are regularly being created and improved. Moreover, structural calculation software are constantly changing and incorporating new methodologies and boundary conditions, according to the progress of the studies and their request.

One of the critical parts of the structural, for design, is the connection between the two pieces of steel. Numerous methods of steel connection execution are currently on the market, and the revolutionary direct fastening technology stands out due to its ease and efficiency compared to the others. The system is based on a threaded stud driven to a steel base material, which will then receive the fastened material and connect both after having the nut tightened.

The structural calculation of the forces transmitted from the main structures to the fasteners demands numerous considerations and criteria. For the tension force, for example, the relation between the Young`s Modulus of the materials is essential for a precise definition of the neutral line coordinate. Likewise, for the shear force calculation, criteria such as the ductility and the stiffness of the materials and the positions of the fasteners on the cross sections are the bases for proper distribution of shear force among them.

The calculation of the exact amount of shear force distributed for each of the threaded studs in the connections of the structure requires high-level tests and great effort. Therefore, accurate assumptions, based on all the relevant parameters of the materials and deep analysis of possible redistribution of shear forces between the studs in critical scenarios, where not all the fasteners are capable to bear shear force, are crucial for conservative and realistic design.

Last but not least, the quality of the next calculation methodologies, to be implemented in the software, is not the only criterion to be considered during the work planning and target definition. The expected benefits of a new calculation methodology should be first aligned with the respective effort required. A right balance between benefit and effort, according to the criteria defined in each project, tends to bring a satisfactory solution.

The scope of this research is based on the development of calculation methodology for a better distribution of shear force, among the fasteners in a steel connection, for later be implemented in the calculation software for direct fastening elements, of the company Hilti AG.

KEYWORDS: direct fastening, fastening on steel, shear force calculation, software implementation and steel connection.

RESUMO

As estruturas de aço são amplamente utilizadas no campo da construção, especialmente devido à sua elevada durabilidade e capacidade de carga. Para apoiar a sua análise e concepção, softwares estão a ser regularmente criados e melhorados. Além disso, os softwares de cálculo estrutural estão constantemente a mudar e a incorporar novas metodologias e condições de fronteira, de acordo com o progresso dos estudos e os seus requerimentos.

Uma das partes críticas da estrutura, para o projeto, é a ligação entre duas peças de aço. Existe actualmente no mercado inumeros métodos de execução de ligações de aço, e a recente tecnologia de fixação directa destaca-se pela sua facilidade e eficiência em comparação com as outras. O sistema baseia-se num parafuso roscado conduzido a um material de base em aço, que receberá então o material de fixação e ligará ambos após ter a porca apertada.

O cálculo estrutural das forças transmitidas das estruturas principais para os fixadores exige numerosas considerações e critérios. Para a força de tração, por exemplo, a relação entre o Módulo de Young dos materiais é essencial para uma definição precisa da coordenada da linha neutra. Do mesmo modo, para o cálculo da força de corte, os critérios como a ductilidade e a rigidez dos materiais e as posições dos fixadores nas secções transversais são as bases para uma distribuição adequada da força de corte entre eles.

O cálculo da quantidade exacta da força de corte distribuída para cada um dos parafusos roscados nas ligações da estrutura requer testes de alto nível e grande esforço. Portanto, hipóteses precisas, baseadas em todos os parâmetros relevantes dos materiais e uma análise profunda da possível redistribuição das forças de corte entre os parafusos em cenários críticos, onde nem todos os fixadores são capazes de suportar a força de cisalhamento, são cruciais para uma conceção conservadora e realista.

Por último, mas não menos importante, a qualidade das próximas metodologias de cálculo, a serem implementadas no software, não é o único critério a ser considerado durante o planeamento do trabalho e definição dos alvos. Os benefícios esperados de uma nova metodologia de cálculo devem ser primeiramente alinhados com o respectivo esforço necessário. Um equilíbrio correcto entre benefício e esforço, de acordo com os critérios definidos em cada projecto, tende a trazer uma solução satisfatória.

O âmbito desta investigação baseia-se no desenvolvimento de uma metodologia de cálculo para uma melhor distribuição da força de corte, entre os elementos de fixação numa ligação de aço, para mais tarde ser implementada no software de cálculo para elementos de fixação directa, da empresa Hilti AG.

PALAVRAS-CHAVE: fixação directa, fixação em aço, cálculo da força de corte, implementação em software e ligação de aço.

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SIMBOLS, ACRONYMS AND ABBREVIATIONS

A – Area [m²]

D – Distance [m]

E – Young's modulus [N/m²]

F – Reaction force [N]

i – Neutral line coordinate [m]

I – Inertial moment [m⁴]

L – Load [N]

LA – Smallest level arm in one direction [m]

M – Moment [Nm]

n – Total number of fasteners

N – Tension force [N]

r – Resultant level arm [m]

V – Shear force [N]

x – Coordinate in x axis [m]

y – Coordinate in y axis [m]

y' – Remaining distance between the edge of the base plate and the centre axis of the fastener [m]

z – Coordinate in z axis [m]

z' – Remaining distance between the edge of the base plate and the centre axis of the fastener [m]

α_{group} – Alpha group coefficient

α_{sf} – Shift of forces factor

β – Dimension ration factor

γ – Eccentricity factor

Δ – Load ratio factor

σ – Stress [N/m²]

ω – Level arm factor

$\emptyset$ – Diameter [m]

ABS - American Bureau of Shipping

BV - Bureau Veritas

DFTM – Direct Fastening Technical Manual

DNVGL - Det Norske Veritas – Germanischer Lloyd

ETA - European Technical Assessment

ET&A - Electronic Tools & Accessories

E2ES - End-to-end solution

Fig – Figure

F&P - Fastening & Protection

ICC ES - International Code Council Evaluation Service

LR - Lloyds Register

MSE – Modular Support Engineering

SGC – Support Group Centroid

1
INTRODUCTION

1.1. MOTIVATION

1.1.1. GENERAL

Steel has been part of human development for a long time: very expensive to produce at the beginning, and normally only used in small and expensive items. It was with the modernization of the steel industry in the 19th century, when the steel construction market leveraged. Steel structures are metal constructions mainly made of structural steel components connected with each other, to carry loads and provide full rigidity. It is one of the main types of building structures and due to its high strength grade, steel construction is reliable and requires less raw material than other types of structures, like concrete and timber.

Currently, steel structures are used for almost every type of construction, including beams, columns and truss (which allow large-span, high and heavy buildings), and welds, bolts and rivets (which are the main responsible to connect to pieces of steel). Construction of large structures, as bridges, warehouses and skyscrapers are normally steel made or have steel in their composition. Some of the main reasons for steel being so common in the civil structural engineering field are:

- Steel is a highly durable metal;
- The load carrying capacity of steel is higher than most of the other structural materials;
- Normally, the construction process with steel is faster;
- The material is versatile, easily fabricated and assembled (disassembled and replaced).

These and other numerous advantages are part of the cause of the presence of steel structures around the globe. Another great cause is the homogeneity of the material, especially in comparison with others in the same field, such as concrete and timber. The high quality of the production, together with advanced calculation methodologies, e.g. structural calculation software, increases the product guarantee of the customers' expectation for the load values.

Calculation software are constantly being updated, for new methodologies, systems and material. The present work will support the implementation of calculation methodologies in steel base material, for the Hilti's calculation software.

1.1.2. COMPANY INTRODUCTION

Eugen and Martin Hilti in Schaan, Liechtenstein, founded in 1941 the company Hilti AG. The enterprise is the world market leader in fastening and demolition technology for the construction field. Hilti products vary from anchoring systems, installation systems, fastening systems, power tools, fire protection systems, measuring tools, and others. With an average number of 60 new products families released per year, the company's product portfolio includes more than 10 thousand products. And it does not only offer the construction tools (Fig.1.1), but also a large variety of software, engineering services and other products, all designed to propose an end-to-end solution (E2ES).

The company is formed by a total of 10 autonomous, and responsible for its own performance and result, business units. Moreover, these 10 businesses are grouped in two business areas: Fastening & Protection (F&P) and Electronic Tools & Accessories (ET&A).

The company employs more than 30 thousand workers around the world, in more than 120 countries. Around 80 % of Hilti's workforce is responsible for sales and directly working with the customers. The strategy of creating sustainable value by leading in terms of relative market share and innovation, as well as differentiation by directly selling their portfolio to the customer, supports the value proposition of the company and all its capital grown during the years.

Fig.1.1 – Overview of Hilti portfolio.

1.2. Overview

1.2.1. Considerations

For the development of the study, a standardised axis coordinate system was defined. In the calculation routine of the Profis MSE software, both global and local coordinate systems are adopted. The global coordinate system defines the position and translation of the body in space and the local coordinate defines how limbs and body segments articulate with the joints, this means it is associated with each node in the model (Peters, Wischniewski and Paul 2019). In this work, both coordinate systems were standardised, to achieve uniform motion, according to Fig.1.2. For the whole reading, the z-axis will be considered as the vertical axis, the direction of the length of the paper and positive from the bottom to the top, and the y-axis will be the perpendicular one, following the direction of the width of the paper and positive from the left to the right of the reader. The x-axis will reflect the axial direction, positive from the paper to the reader. For the clarity and proper understanding of the work, the term *load* will be used to refer the external applied load in the structure and the term *force* will refer to the reaction for force in the fasteners.

The concept of activation will be defined in the next chapter of the study. Important for the reading at this point is the capability of identifying which fasteners are properly inserted in the base plate hole, so that they have contact with the base plate and can bear shear force, and which are not. This concept is detailed in Fig.1.3, where the red circles identify a fastener which is able to bear shear force, and a grey circle defines a fastener which is somewhere in the middle of the base plate's hole and does not have proper contact with the base plate to receive shear force.

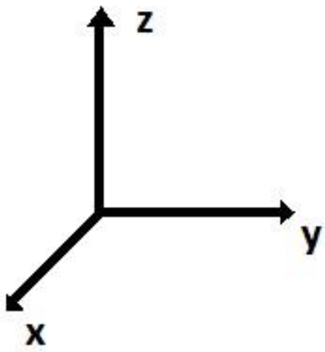

Fig.1.2 – Global and local axis coordinate systems.

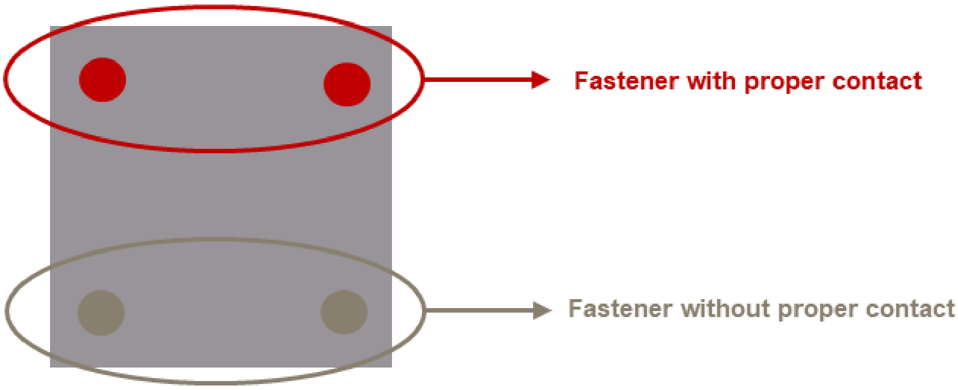

Fig.1.3 – Definition of fasteners with and without proper contact with the base plate.

1.2.2. PROJECT TIMELINE

The work package, the time frame and the weekly targets of the project were defined at the beginning of the research. Ideal to guide, the weekly targets were essential to clarify the step by step during the development and assure that each deadline was respected. The work package was defined in six stages:

1. Investigation comprehension;
2. Framework of the project;
3. Physical test;
4. Cases study;
5. Analysis;
6. Implementation.

Each of the states was determined based on being responsible to answer the main block of questions, raised at the beginning of the research. The main questions started the work planning procedure and were crucial for the development of a structure and lean research. The base for the creation of the six stages were:

Investigation comprehension

- What is the investigation about?
- Why is it required?

Framework of the project

- How it will be done?
- Which are the objectives?
- When is the deadline?

Physical test

- How will be the tests?
- What is important to extract from the results?
- Which are the base assumptions? And based on what they will be built?

Cases study

- With which tools will the analysis be performed?
- Which are the relevant parameters?

Analysis

- Which are the boundary conditions?
- What is the procedure to formulate a new methodology?
- What are the expected improvements?

Implementation

- Which are the requirements for a proper software implementation?
- What comes next?

Therefore, a Gantt chart was created (Fig.1.4), together with the work package Table 1.1:

Table 1.1 – Work package, time frame and weekly target of the project.

Work Package	Week	Time Frame
1. Investigation comprehension 1.1. Get Familiar with Profis MSE calculation software; 1.2. Understand the current calculation methodology; 1.3. Identify critical cases and possible rooms for improvement.	50/2021 51/2021 2	3 weeks
2. Framework of the project 2.1. Determine the table of content; 2.2. Establish the objectives of the work and identify the base assumptions; 2.3. Plan the project timeline, the work package and the weekly targets;	3 4 5	3 weeks
3. Physical test 3.1. Prepare the physical tests and their procedure; 3.2. Analyse the results and assessments.	6 7	2 weeks
4. Cases study 4.1. Interpret the relevant parameters for the calculation methodology; 4.2. Define the cases study and build the concept of sub-cases.	8 9	2 weeks
5. Analysis 5.1. Define the boundary conditions for the new calculation methodology; 5.2. Analysis of the calculation methodologies under different boundary conditions; 5.3. Build a formulation to calculate shear force; 5.4. Implement all the relevant criterions in the formulation; 5.5. Identify the improvements of the new calculation methodology;	10 11 12 13 14	5 weeks
6. Implementation 6.1. Understand the requirements for a proper software implementation; 6.2. Determine possible approaches and their respective pros and cons; 6.3. Hand over the technical data for Profis MSE; 6.4. Characterize the outlook for the next researches.	15 16 17 18	4 weeks

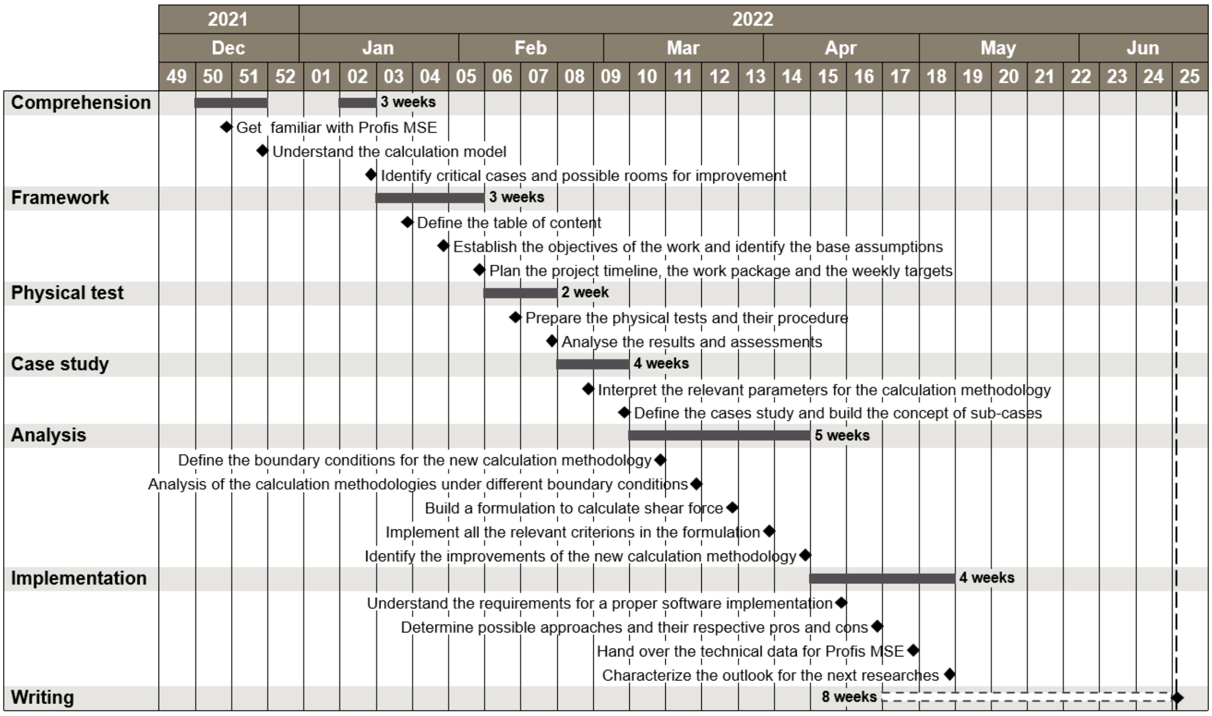

Fig.1.4 – Gantt chart of the project planning.

1.3. STRUCTURE OF THE WORK

This research is divided into seven chapters, having the first and the last one dedicated to the introduction and to the conclusion, respectively.

The second chapter will address the concept of the direct fastening technology, presenting the components and different systems for fastening, as well as the applications and the advantages over the competition. Codes and approvals related to the system are also mentioned. At the end, the understanding of a structural calculation software will be presented, likewise the methodology behind the Profis MSE and an assessment of the results currently provided by the Hilti calculation software.

The third chapter shows the fundamental data and criteria used for the formulation of the base assumptions adopted in the work. The concept of the physical test performed during the research, as well as an analysis of the results. Later, the chapter introduces to the reader the calculation model used in the Profis MSE for shear force, specifying all the load in the structure that can be transmitted as a shear force to the fasteners, and their formulation. Moreover, the case study concept is explained, likewise the approach adopted in this work to define the case studies and their boundary conditions.

The fourth chapter brings the proposed new calculation methodology for the Hilti calculation software. Starting with the definition of the formulation based on case studies analysis, through a deep dive into the relevant criteria for all the steps of the procedure.

The fifth chapter clarifies the implementation procedure of a new formulation into a calculation routine, as well as the different possible approaches to do it successfully, together with an assessment of the benefit versus the effort required by each of them.

1.4. KEY TARGETS

Structural calculation software is increasingly used as a support for engineers to analyse and design structures. Therefore, efficient calculation methodologies are essential to provide accurate and realistic results.

In this context, the first objective of this thesis is to investigate and understand the existing calculation methodology for fasteners and Typicals in Hilti calculation software, in the sense of understanding the procedure and identifying possible improvements.

The second objective of the thesis is the development of a new methodology, for a more realistic (and also properly conservative) distribution of shear force among the fasteners. This methodology has to be validated to all currently available structures in the software and for the next ones to come.

The last objective of the work requires a deep understating of the requirements for a proper software implementation. The final target is to guarantee that the content developed during the research can be feasibly implemented in the calculation software.

2
DESIGN OF DIRECT FASTENING ON STEEL MEMBERS

2.1. DIRECT FASTENING TECHNOLOGY

2.1.1. GENERAL

Direct fastening technology is a system in which a hardened nail or stud is driven into steel, concrete or masonry by a piston-type tool. According to Shan and Su (2019), among the methods to connect two steel components, direct fastening is well known for its effectiveness. Due to the labour and time efficiency, steel structures have been widely used and the type of connection is a key factor to guarantee the efficiency. Direct Fastening technique was first applied in 1950`s and since then, it has been innovating and making this system more productive, reliable and safer.

Other methodologies for similar applications, such as welding, bolting ad clamping, have been on the markets longer, and together with direct fastening, are the main methods to connect two steel components. In the following scheme (Fig. 2.1), there is a summary of the direct fastening features versus the concurrent methodologies.

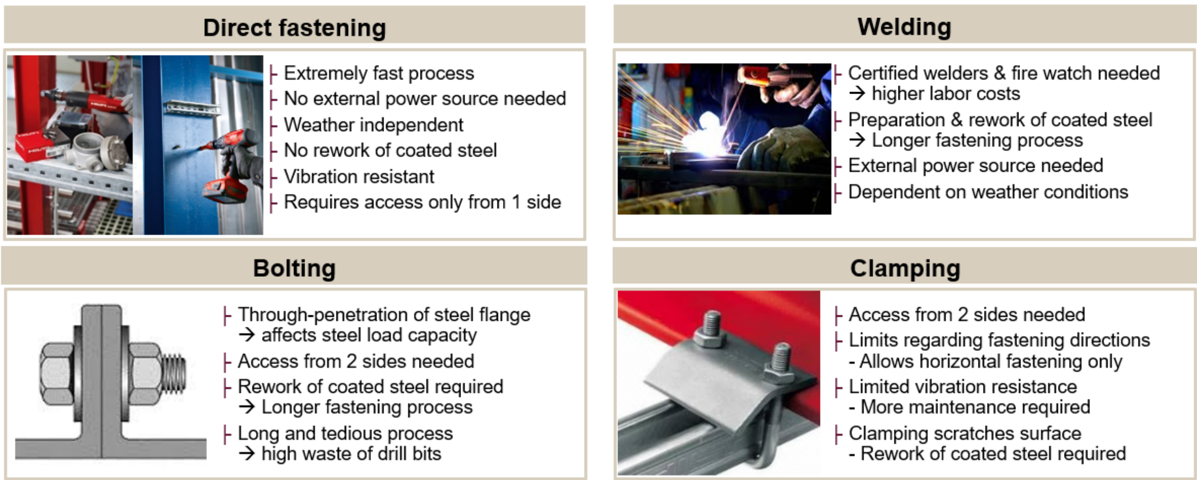

Fig.2.1 – Main characteristics of direct fastening system and the concurrent.

Among the different anchoring mechanisms responsible for joining steel plates by direct fastening, such as fusing, soldering, clamping and keying, the last two are especially important for the yield strength of the connection.

The direct fastening system consists of three main components: a fastener, driving energy and the tool.

2.1.2. System components

2.1.2.1. Fastener

Fasteners are hardware devices, normally made of steel, which are used to join or hold materials together. According to Hilti's Direct Fastening Technical Manual (DFTM) (Corporation 2022), fasteners can be classified into three general types: nails, threaded studs and composite fasteners. As the scope of this research is the threaded studs, essentially nails with threaded upper section instead of a head, they will be called fasteners during the work. The main criterion to framework them is the configuration of the tip.

Fasteners are described as a sharp tip or blunt tip, as presented in the Fig.2.2**.** The shape of the tip is directly linked with the methodology used for fastening and the holding mechanisms (friction, fusion, and others) between the fastener and the base material. Sharp tip fastening is a technology where the fastener is driven directly to the base material, as a one-step solution. The resilience of the displaced base material as the fastener is being driven exerts a clamping force on the surface of the fastener. The revolutionary blunt tip fastening cannot be done in one-step and requires a previous phase: surface preparation. This phase can be either executed as a pre-drilled hole in the base material or by cleaning the surface (and coating) for later steps (Hilti 2019).

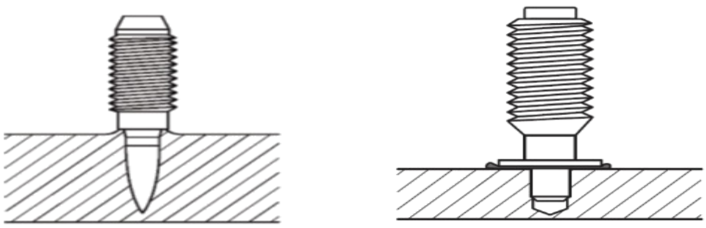

Fig.2.2 – Sharp tip and blunt tip fasteners' configuration, respectively.

The manufacturing process for steel fastening normally starts from cutting the wire to the length and head forming. Both carbon and stainless steels have the same first step, but the differ during the flow, as the stainless steels fasteners don't require thermally hardened and others process. A simplified scheme of the manufacturing process flow for fasteners made of carbon steel is presented below in the Fig.2.3.

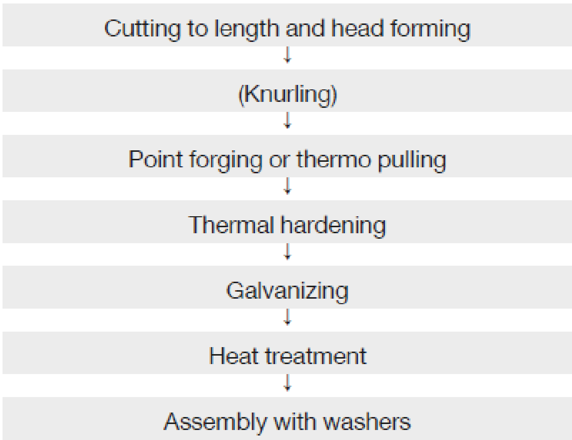

Fig.2.3 – Manufacturing process' flow for carbon steel fasteners.

2.1.2.2. Driving energy

The original energy source used by the tools to drive the fastener towards the base plate is powder. The powder-actuated tools normally used cartridges to store powder, and when they have their trigger pressed, the powder is mobilized to explode and generate energy to push the piston and after the fastener.

Gas-actuated tools were posteriorly introduced, where instead of powder, the main source of energy comes from a pressurized gas can.

With a similar concept, battery-actuated tools were also introduced into the market. For this equipment, two springs are connected and when tool has its trigger pressed, from the energy of the battery, the springs move and push the piston towards the fasteners.

While the originally used energy source was powder, gas and battery driving energies have been added as more recent innovations for the system.

2.1.2.3. Tool

Besides the driving energy, the method used to drive the fastener to the steel base material might be the greatest distinction between the tools.

The current methods available on the market are:

- Screw tools: the tool screw the fasteners towards the pilot hole previously made;
- Drive tools: the tool drives the fasteners towards the pilot hole previously made;
- Welding tools: the tool weld the fasteners on the steel surface previously cleaned.

2.1.3. Applications

2.1.3.1. General

The main application for the direct fastening system is directly linked to the base material and to the purpose of the fastening. The main applications are:

- Fastening on concrete: used on formwork of concrete walls, wall ties, wire mesh and water membranes;
- Insulation: used during the installation of insulation in walls, ceiling and foundation;
- Decking: used when fixing metal roof decks into steel structures and siding;
- Fastening on steel: used on grating floor fixing, multi-purpose services that requires fastening on steel base material and electrical connections;
- Track and ceiling: used when setting drywalls and suspended ceilings;
- Fastening on wood: used when wood is the base material.

2.1.3.2. Fastening on steel

Fastening on steel is the main application of this dissertation and it can be generalized to all fastening methodology applied to steel base material.

The scope of this work is based on steel structures, called Typicals, attached to steel base materials. The understanding of the influence of a steel structure applying stress, and consequently strain, on another steel base material, is crucial for this research and it will be studied later, in this chapter.

The current ways of attaching steel structures available on the market, as previous mentioned, are direct fastening, welding, clamping and through-penetration bolting. The direct fastening method is particular, due to the boundary conditions relevant for load bearing capacity of the involved fasteners. The analysis of these boundary conditions will be essential for understanding the research.

2.1.4. Typical

Typicals are steel frame modular installation systems. Destinated to receive a huge range of loads, the structure has countless support applications, such as:

- Piping (Fig.2.4);
- Ventilation;
- Electrical (Fig.2.5);
- Sprinklers;
- Others.

The shape of the Typical is also a parameter with numerous combinations, and the reason for the name. They can be simple structures, such as a cantilever, to more complex ones, such as a L-frame or a T-post, as described in the Fig.2.6. The relevance of the shape of the Typical will be crucial in the next chapters to understand their influence on the forces.

In this work, it is important to emphasize the part of the Typical which has the contact and transfer loads to the fasteners: the base plate (or bracket). In the Fig.2.7, it is possible to identify the base plate of a cantilever Typical attached to steel column by the threaded studs.

The current base plates available differ in the following parameters:

- Number of holes to be filled by fasteners: from 1 to 6;
- Shape of the holes: rounded and slotted;
- Shape of the base plate: square or rectangular;
- Position of the holes.

The mentioned parameters have a crucial relevance for the presented study, and they will be deeply analysed in the next chapters. Some examples of the current base plates available and the differences between them for each parameter can be seen in the Fig. 2.8:

Fig.2.4 – Piping application with Hilti's Typical structures.

Fig.2.5 – Electrical application with Hilti's Typical structures.

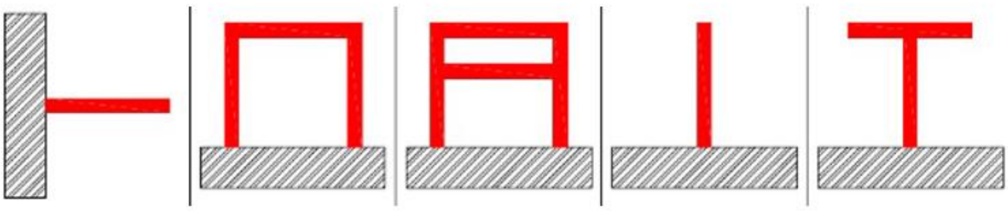

Fig.2.6 – Common Typical structures available in the market.

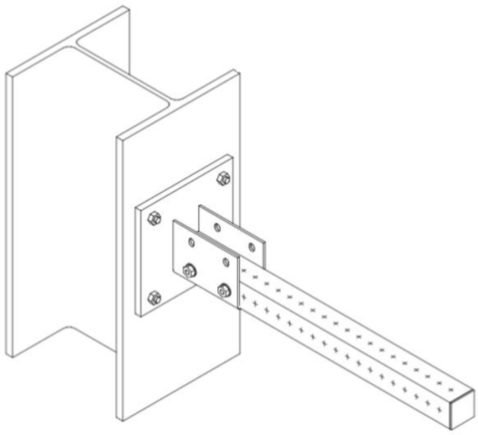

Fig.2.7 – Cantilever Typical attached to a steel column by direct fastening technique.

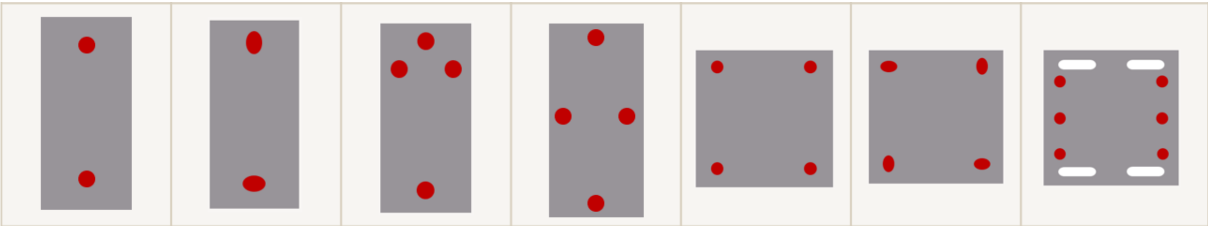

Fig.2.8 – Cross section model of base plates available in Profis MSE.

2.2. CODES AND APPROVALS

Direct fastening systems are non-standard construction solutions. Their products require specific approvals to allow its use. Fasteners from Hilti are certified by various bodies (Fig. 2.9) depending on their intended usage. For example, type approvals for one Hilti fastener solution, X-BT fasteners, are:

- American Bureau of Shipping (ABS 2021);
- Det Norske Veritas – Germanischer Lloyd (DNVGL 2021);
- Lloyds Register (LR 2020);
- Bureau Veritas (BV 2019);
- Russian Maritime Register of Shipping (PC 2020);
- International Code Council Evaluation Service (ICC-ES 2021);
- UL Product IQ (UL 2021).

Also relevant for this work on fastening on steel, are the Eurocode 3 part 1 (EN 1993-1-1 2005), part 8 (EN 1993-1-8 2005) and ETAs.

The European Technical Assessment (ETA) offers manufactures a voluntary route to CE marking, providing an independent Europe-wide procedure for assessing the essential performance characteristics of non-standard construction products, normally when the product is not fully covered by a harmonized standard. (EOTA 2022)

An example of an ETA that covers the mentioned fastener, is the ETA-20/1042 (2021) (Fig. 2.10), which has the following trade name of the construction product: Hilti threaded studs X-BT-MR and X-BT-GR (ETA 2021).

Fig.2.9 – Common approval bodies for fasteners solutions.

CE
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Hilti AG FL-9494 Schaan
Hilti-DX-DoP-008
ETA-20/1042
EAD 333037-00-0602
0672
Threaded studs for connection of materials to structural steel

Fig.2.10 – European Technical Assessment for Hilt fastener solution.

2.3. STRUCTURAL CALCULATION SOFTWARE FOR FASTENERS

The Hilti's calculation software Profis Modular Support Engineering (Profis MSE) was used to develop this research. The software is also destinated, among the mentioned methods to connect to steel members, to direct fastening as solutions to attach the modular supports (Typicals, bracket and others) on the base materials. Profis MSE provides the front end for the calculation. The Hilti's calculation software works together with RSTAB Dlubal, another structural calculation software, responsible for the calculation kernel.

RSTAB is a structural analysis and design software from 3D beam, frame or truss structure calculation and other spatial frameworks. RSTAB calculates under linear and nonlinear boundary conditions, to determine internal forces, deformations, and support reactions of general framework structures (Dlubal 2013).

After modelling the structure, adding the required information, e.g. force, and executing the calculation in Profis MSE, all the data is forwarded to RSTAB, where the first steps of the calculation are done. The part of the calculation destinated to Profis MSE starts when it receives from RSTAB the forces and the moments on all the base plates of the structure. The distribution of forces and moments from the base plate to the fasteners is completely done by Profis MSE. At the end, a report is issued by the Hilti's calculation software. The whole workflow is shown in the Fig.2.11

The base plate might receive forces and moments in three directions, but due to simplification purposes, Profis MSE assumes the fastener is capable to support only the forces, as presented in the Fig.2.12.

As result of the calculation, the fasteners supporting the structure presents:

- Tension force;
- Shear force on Z direction;
- Shear force on Y direction.

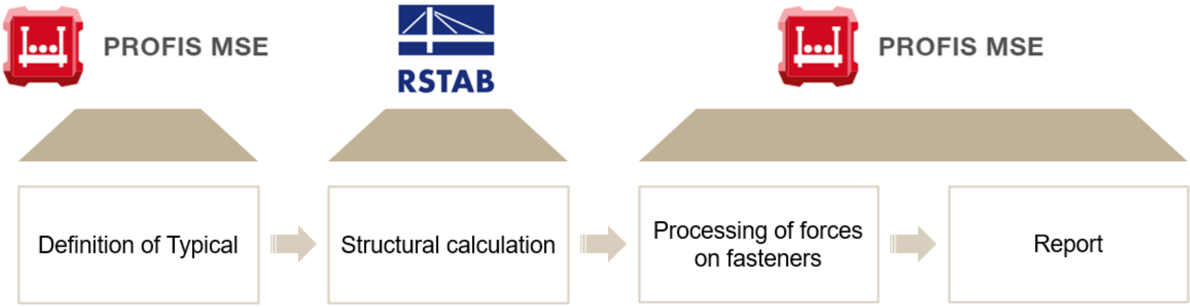


Fig.2.11 – Fasteners and Typicals calculation's workflow.

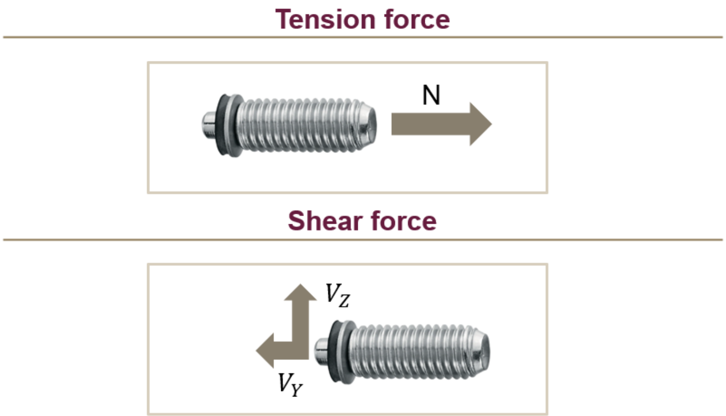


Fig.2.12 – Vector forces supported by the fasteners, in the Profis MSE software.

2.4. Existing calculation methodology

2.4.1. General

As previously mentioned, the software Profis MSE considers the fastener as capable to support only forces. The calculation methodology for tension force is based on the equilibrium of the structure, while the methodology for shear force is an evenly distribution base on the total number of fasteners, together with a resistance reduction factor applied for the load capacity calculation.

2.4.1.1. Tension force

The static equilibrium to calculate the tension force applied to a fastener, due to forces and moments on the base plate, starts with an assumption of a coordinate (i) for the neutral axis (Fig.2.13).

For explanation purposes, the following example in the Fig.2.14 will be considered. A cantilever Typical with a distributed load applied to its entire length, and geometry indicated in the figure.

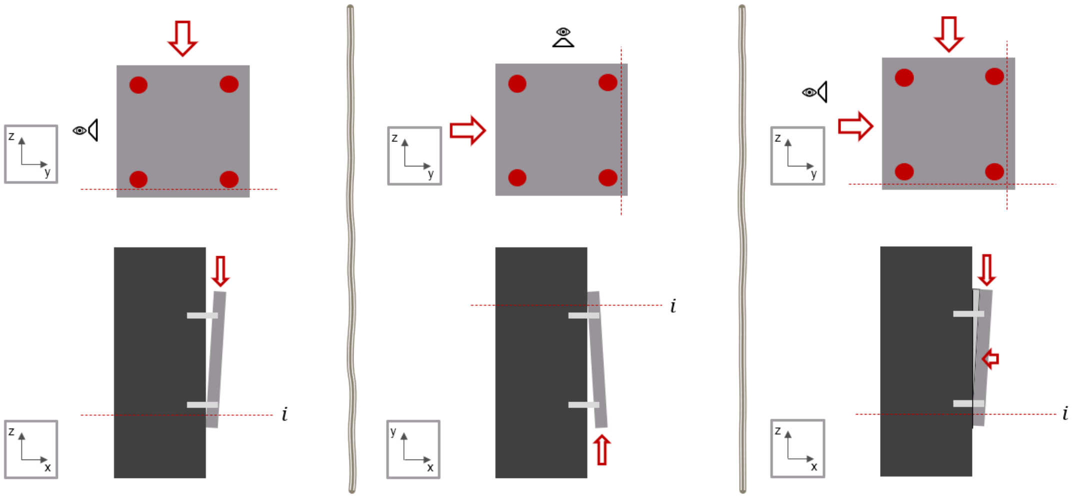


Fig.2.13 – Behaviour of neural line coordinate under different load directions.

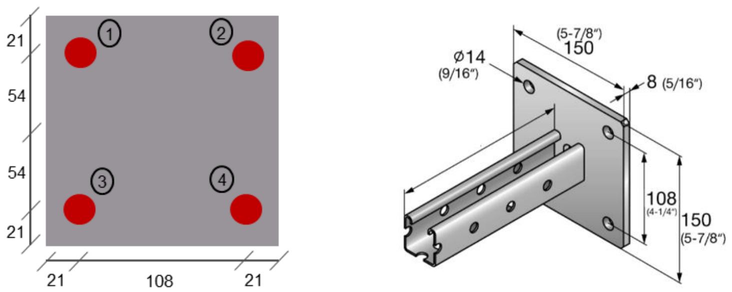


Fig.2.14 – Example of the geometry of a cantilever Typical (dimension in mm).

The second step of the process is the calculation of the cross-section stiffness, in both compression and tension zones. The neutral line for this structure is normally nearby the bearing edge of the base plate, due to both materials (steel) compressing each other have similar Young's modulus, as shown in the equation (2.1). The contribution for the resistance on the compression zone will be normally only composed by the contribution of the base plate, because the neutral line will might not reach the coordinate of the fasteners. For that, the code calculates the area of the theoretical compressive zone and later the inertia moment.

$$Young`s\ modulus\ ratio = \frac{E_{typical}}{E_{base\ material}} \approx 1 \tag{2.1}$$

The same concept is applied to the tension zone, but here the contribution comes only from the fasteners. The code calculates the area of all fasteners and afterwards their inertia moment (equation 2.2), based on the theoretical neutral line. The software calculates then the total inertia moment of the cross-section.

$$I_{total} = I_{compression} + I_{tension} \tag{2.2}$$

The next steps are the calculation of the stress (equation 2.3), force (equation 2.4) and moments (equation 2.5) for both zones. For the compression zone, the calculation is the following:

$$\sigma_{compression} = \frac{M_{Ed}}{I_{total}} \cdot i \tag{2.3}$$

$$F_{compression} = \sigma_{compression} \cdot \frac{A_{compression}}{2} \tag{2.4}$$

$$M_{Rd,compression} = F_{compression} \cdot \left(\frac{2}{3} \cdot i\right) \tag{2.5}$$

Important to notice, that bases of the calculation are the moment applied on the base plate and the assumption of the neutral line's coordinate.

For the tension zone, a similar calculation is applied for the fasteners. After having the total resistance moments (equation 2.6) from the compressive and tension zone, a ratio is calculated by the following law demonstrated in the equation (2.7).

$$M_{Rd} = M_{Rd,compression} + M_{Rd,tension} \tag{2.6}$$

$$M_{Ratio} = \frac{M_{Ed}}{M_{Rd}} \tag{2.7}$$

When the ratio converges to a satisfactory value, normally around 0.99 and 1.01, the iteration process stops, and the equilibrium is assumed as achieved. As a result of this iteration, the software reaches a satisfactory position for the neutral line and returns to the users the tension force on the fasteners.

2.4.1.2. Shear force

For the shear force, the assumptions considered in the software are simplified. Currently, when applying load in Z and/or Y direction (Fig.2.15), the software will evenly distribute between all fasteners, as shown in the table (2.1).

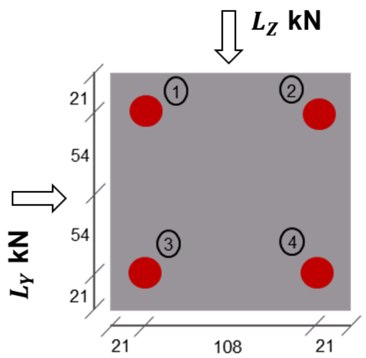


Fig.2.15 – Vertical and horizontal loads applied in a four holes base plate (dimension in mm).

	V_Y [kN]	V_Z [kN]
1	$L_Y/4$	$L_Z/4$
2	$L_Y/4$	$L_Z/4$
3	$L_Y/4$	$L_Z/4$
4	$L_Y/4$	$L_Z/4$

Table 2.1 – Results provided by the existing methodology of equal shear force distribution.

This concept of an equal distribution works satisfactory good for the cases where all the fasteners are made of the same material and were fastened in a similar way, reason to consider the assumption of a similar stiffness between the fasteners.

A third factor crucial to consider a realistic equal distribution of shear forces between the fasteners is the ductility of the fasteners. In reality, the holes where the fasteners are inserted do not have the same diameter as the main diameter of the fastener. For workability purposes, the diameter of the holes must be greater enough than the diameter of the fasteners. For the cases where the fasteners cannot guarantee enough ductility, consider that all the fasteners are in contact with the base plate and are able to bear shear force, might not provide realistic results anymore.

2.4.2. Utilization and activation concepts

Utilization of a single fastener, or a group of fasteners, is a measurement of the load capacity of the fasteners, which can be calculated as the relation between the force applied to the fastener and the resistance of the fastener, as per the equation (2.8).

$$Utilization = \frac{Force}{Resistance} \tag{2.8}$$

As the fasteners, on the Profis MSE calculation, are only able to bear forces, the equation above can be extrapolated to the equation (2.9), according to the equation (2.10):

$$Utilization = \frac{N_{Ed}}{N_{Rd}} + \frac{V_{Ed,res}}{V_{Rd}} \tag{2.9}$$

$$V_{Ed,res} = \sqrt{\left(V_{Ed,y}\right)^2 + \left(V_{Ed,z}\right)^2} \tag{2.10}$$

The activation is a concept concerning the capability of a fastener to bear load or not. For tension force, the critical factor that guarantees the capability of a fastener is the presence of the nut. All the fasteners, in Profis MSE, are considered activated fasteners for tension force. For shear force, the critical factor is the contact between the edge of the fastener and the base plate. Proper mechanical contact is crucial to transfer load from the base plate to shear force on the fasteners.

2.4.3. Shear load capacity reduction factor

The currently methodology used in Profis MSE to cover the distribution of shear force among fasteners with different ductility is the alpha group coefficient (α_{group}). After evenly distributing the shear force for all the fasteners, the alpha group coefficient is applied to reduce the shear resistance of the fastener (equation 2.11):

$$Utilization = \frac{N_{Ed}}{N_{Rd}} + \frac{V_{Ed,res}}{\alpha_{group} \cdot V_{Rd}} \tag{2.11}$$

When a fastener, under load, deforms sufficiently to guarantee that all the other fasteners will have contact before the failure of the first fastener, the α_{group} assigned for this ductile fastener is equal to 1.

For fasteners with smaller ductility, where a proper contact between all the fastener and the base plate cannot be guaranteed anymore, the α_{group} assumes values between 1 to 0.

2.4.4. Critical cases

Currently, the α_{group} used in Profis MSE for a fastener with the lowest ductility has the value of 0.33. This value comes from the analysis of the most critical base plate case in the software, with 6 holes (Fig.2.16).

When the ductility of the fasteners cannot guarantee a proper mechanical contact of all of them with the base plate, cases where not all the fasteners are activated for shear force might occur.

To define the current methodology of capacity reduction factor for shear load ($\alpha_{group} = 0{,}33$), the assumption of two activated fasteners for shear force was the one used. As the base plate with the maximum number of fasteners available in Profis MSE is 6 and the assumption of the minimum number of fasteners activated for shear force is 2 fasteners, the current coefficient follows this rule and reduces the resistance (or increases the force) of them by 3 times.

The coefficient is applied to all cases and structures fastened with this type of fastener. In cases with base plates for only two fasteners also have the alpha coefficient applied, assuming theoretically that one third of the two fasteners are the only activated for shear force and providing conservative results.

On the other hand, when analysing the same critical case used as a base to define the current $\alpha_{group} = 0.33$, under load in Y and Z direction, and selecting the two top fasteners as the activated ones for shear force (Fig. 2.16), it is feasible to calculate the internal force on both fasteners, based on the equations of static. To guarantee equilibrium of the forces in Z direction, the equations (2.12), (2.13) and (2.14) needs to be followed.

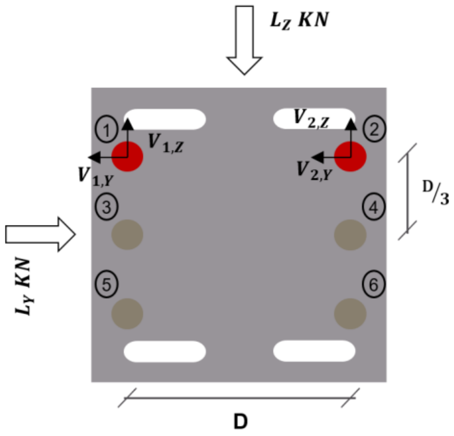


Fig.2.16 – Scheme of the force in the activates fasteners, when applying horizontal and vertical loads.

$$\sum Load_Z = 0 \tag{2.12}$$

$$V_{1,Z} + V_{2,Z} - L_Z = 0 \tag{2.13}$$

$$V_{1,Z} + V_{2,Z} = L_Z \tag{2.14}$$

For the load in Z direction, due to the symmetry of the load applied in the middle of the two fasteners, it can be assumed the Z component of the force on both fasteners is the same (equation 2.15).

$$V_{1,Z} = V_{2,Z} = \frac{L_Z}{2} \tag{2.15}$$

Initially, Profis MSE distribute the load L_Z equality for all the fasteners, which would result in a force of $L_Z/6$ for all of them. As only two fasteners are considered activated on this analysis, the force on the fastener should change to $L_Z/2$, three times higher than the initial equal distribution defined by the software. As an assessment, it is possible to conclude that, until this point, the current alpha group coefficient is covering the assumption of only two activated fasteners.

For the load applied in Y direction, a similar concept rules, according to the equations (2.16), (2.17) and (2.18):

$$\sum Load_Y = 0 \tag{2.16}$$

$$V_{1,Y} + V_{2,Y} - L_Y = 0 \tag{2.17}$$

$$V_{1,Y} + V_{2,Y} = L_Y \tag{2.18}$$

In this case, the load is not applied between the centre axis of both activated fasteners. For the analysis of L_Y load on the Y direction, an assumption base on stiffness is applied. As both fasteners are made of the same material and it is considered they are fastened in the same way, it is feasible to assume each of them will bear half of the load (equation 2.19):

$$V_{1,Y} = V_{2,Y} = \frac{L_Y}{2} \tag{2.19}$$

Here again, the same assessment concerning the method of the alpha group coefficient applies and with this methodology, until now, the software is now covering the assumption of only two fasteners are activated for shear force.

In the last step of this analysis, the third equation of static is applied and the sum of moments in any point should provide equilibrium to the structure. When calculating the sum of moments counter clockwise, for this example on the centre axis of the fastener number one, as done on the equations (2.20), (2.21), (2.22) and (2.23) below, it is possible to notice that the structure does not have equilibrium.

$$\sum Moment = 0 \tag{2.20}$$

$$V_{2,Z} \cdot D - L_Z \cdot \frac{D}{2} + L_Y \cdot \frac{D}{3} = 0 \tag{2.21}$$

$$\frac{L_Z}{2} \cdot D - L_Z \cdot \frac{D}{2} + L_Y \cdot \frac{D}{3} = 0 \tag{2.22}$$

$$L_Y \cdot \frac{D}{3} \neq 0 \tag{2.23}$$

Due to the eccentricity between the load in Y direction and the centre axis of the fasteners, there is a tendency of rotation on the base plate, which is better visualized when isolating the horizontal load and placing the reaction force on the fasteners in the right direction (Fig.2.17).

This “new moment” created by this eccentricity is then supported by components of force on the fastener in the Z direction. Calculating the same sum of moments as previously, but only considering the horizontal force (equation 2.24, 2.25 and 2.26):

$$\sum Moment = 0 \tag{2.24}$$

$$L_Y \cdot \frac{D}{3} - V'_{2,Z} \cdot D = 0 \tag{2.25}$$

$$V'_{2,Z} = V'_{1,Z} = \frac{L_Y}{3} \tag{2.26}$$

After analysing the structure with the laws of static, the base plate has equilibrium, but the current methodology of the alpha coefficient does not cover this scenario (Fig. 2.18).

The resultant of the force on the activated fasteners, or at least in one of them, will be higher than 3 times the resultant of shear force when considering an equal distribution, due to the addition of the new component. On one hand, a constant reduction coefficient, used for all cases, for the resistance of the fasteners provides high conservative results for simple structures. On the other hand, as it was explained, the methodology does not cover more complex structures.

The scope of this dissertation is based on defining a better methodology to distribute the shear force for the fasteners.

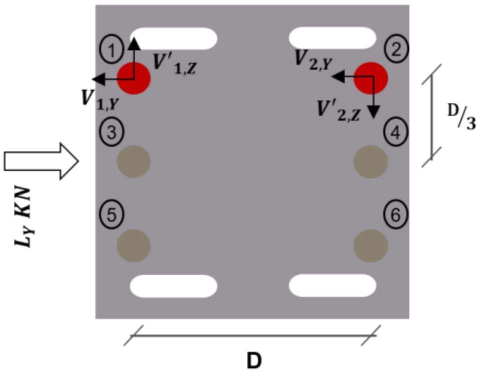


Fig.2.17 – Scheme of the force in the activates fasteners, when applying only horizontal load.

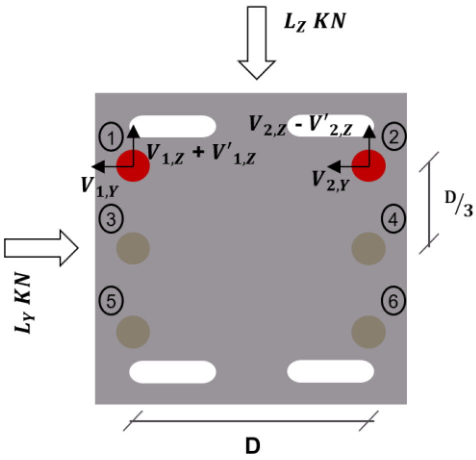


Fig.2.18 – Scheme of the force in the activates fasteners, considering the eccentricity.

3
DEVELOPMENT OF A TYPICAL AND FASTENER CALCULATION MODEL

3.1. GENERAL CONSIDERATIONS

The consideration of all fasteners activated for shear force might not provide satisfactory results for all threaded studs available in calculation software, as discussed in the previous chapter.

In this chapter, the reader will first understand the concept of ductility, how this parameter can be measured on fasteners and the relevance of this information for the base assumptions of this work. Later, it will be presented an overview of the base assumptions and it will end with the explanation and assessment of the key targets of the research.

3.2. FUNDAMENTAL DATA

According to Park (1989), the term “ductility” is used to mean the capacity of a structure, under load application, to undergo large deformation without reduction in strength. Materials with this characteristic are normally associated to ductile ruptures, differently to fragile ruptures, where the material fails without presenting relevant signs. Among the numerous procedures for the assessment of ductility of steel connections, the recent papers involve the identification of the yield of the material and analyses of force-displacement diagrams (Simões da Silva and Girão Coelho 2001). A similar methodology will be adopted in this work.

During the performed work, physical tests with fasteners and Typicals were made, and they were crucial to understand the ductile behaviour of the fastener. The tested components were Typicals fastened, with 10mm diameter threaded studs, on a steel structure S355, with conventional coating and 20 mm thickness. Each base plate was fastened with four fasteners (Fig.3.1) and mounted in a similar way to the real usage, in the attempt to consider the distribution of the applied loads and self-weight, among the fastener, as realistic as possible. In the Fig. 3.2 and 3.3, a representation of the test configuration and the machine are shown.

Fig.3.1 – Representative model of the test assembly.

Fig.3.2 – Representative configuration of the test and machine used.

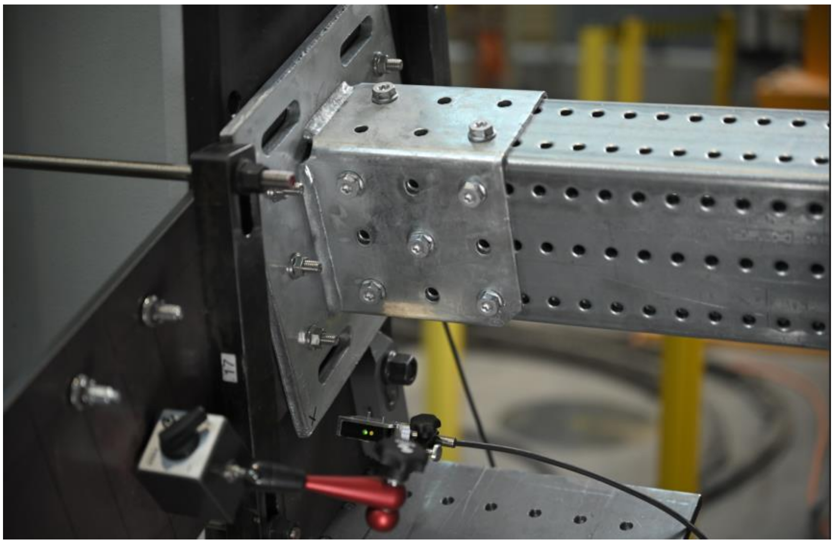


Fig.3.3 – Representative configuration of the fasteners and the base plate.

The three steel base plates were denominated according to the respective position, respectively Pos. A, Pos. B and Pos. C. The initial distances between all the fasteners, before the deformation, were measured and in Fig.3.4 it is possible to identify these distances per base plate position and per fasteners, for example, A1-4 means the distance between the fasteners number 1 and 4, in the base plate A. On each of the Typicals was applied a vertical load until the failure of the structure.

During the tests, the position of the base plate and the fasteners were measured continuously. The distance between the fasteners, after the structure is deformed due to the load application, has slight differences which are shown in Table 3.1. Lastly, the whole deformation of the structure has a function of the applied load, and it is presented in Fig.3.5.

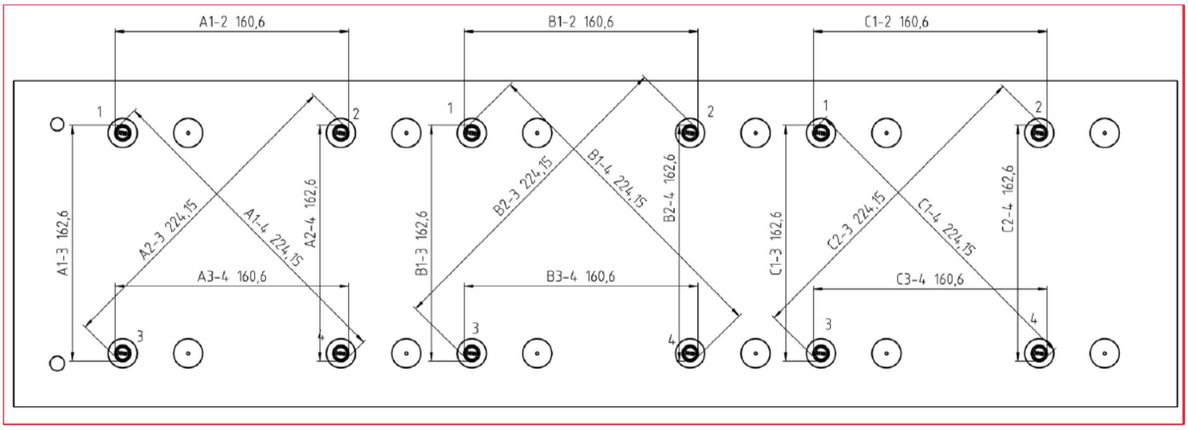


Fig.3.4 – Initial distance between the fasteners.

Table 3.1 – Distance between the fasteners, after load application.

Pos. A		Pos. B		Pos. C	
A1-2 →	160.94	B1-2 →	160.8	C1-2 →	160.66
A3-4 →	160.7	B3-4 →	160.5	C3-4 →	160.4
A1-3 ↑	162.67	B1-3 ↑	162.52	C1-3 ↑	162.2
A2-4 ↑	162.73	B2-4 ↑	162.65	C2-4 ↑	162.4
A2-3 ↗	223.84	B2-3 ↗	223.6	C2-3 ↗	224.1
A1-4 ↖	224.05	B1-4 ↖	223.7	C1-4 ↖	224.05

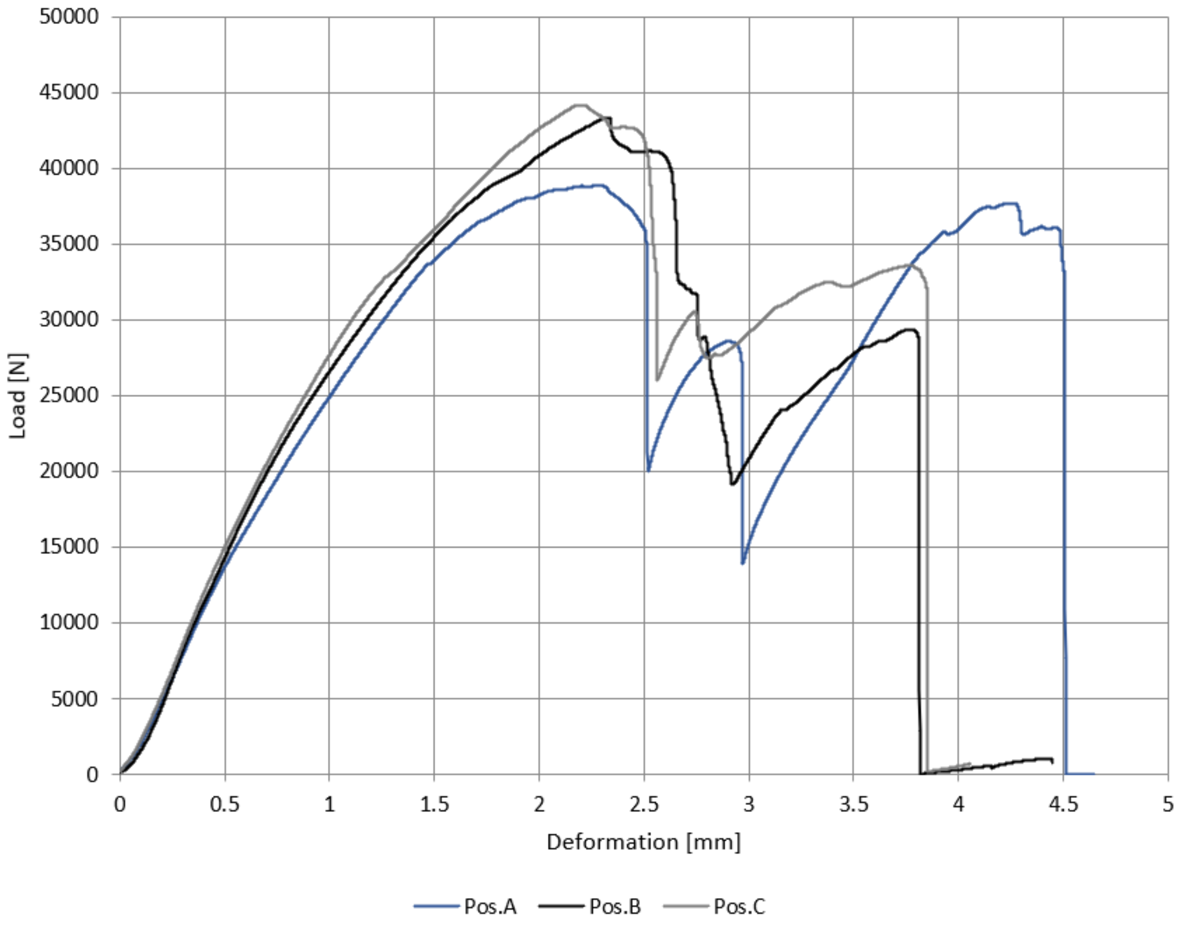


Fig.3.5 – Chart of the structure’s deformation under load application.

The chart (Fig. 3.5) gives important information for the definition of the base assumption. As it is shown in the diagram, the Typical structure with four fasteners attached to the steel base material follows an elastic rule until around 1.5 mm, where a load of nearly 35 kN is applied and no failure occurs.

Important to identify, with the provided information, is the ductility of the fasteners, in other words, how much they can deform under load application until the failure. This information is crucial to analyse the feasibility of considering that all fasteners will have contact with the base plate and bear shear force, until the first threaded fails. If in a first moment, only two fasteners are in contact, would the deformation of 1.5 mm be enough to guarantee that the other fasteners will also have contact and share the whole shear load, or the fastener will break before? As shown in the Fig.3.6, the initial position of the fasteners 1 and 4, of the base plate A, are not the same, when comparing to the centre of the base plate hole. Only under the self-weight, according to the figure, the fastener 1 has a higher probability to bear shear force than the fastener 4.

Fig.3.6 – Initial position of the fastener 1 and 4, of the base plate A.

3.3. BASE ASSUMPTIONS

After analysing and understanding the behaviour of the fasteners' ductility, new assumptions for the number of fasteners capable to bear shear load needs to be defined and replace the previous one.

As the first assumptions come from the most conservative side, the base assumption of this work started with the consideration of only one fastener is capable to bear shear force. The first step to validate the feasibility of this assumption and proceeding with the analysis is to guarantee the structure can reach equilibrium with only one fastener supporting the shear force.

As it can be seen the Fig. 3.7, the laws of static equilibrium were applied to the 2D structure with only one support and the statement is clear: it is a hypostatic structure and will not be able to guarantee equilibrium with only one support.

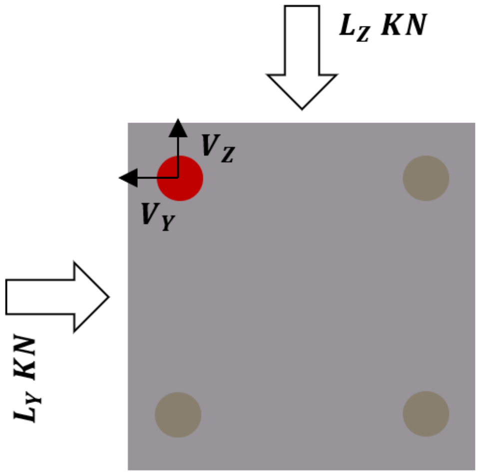


Fig.3.7 – Hypostatic base plate with 4 fasteners, but only one activated.

After having the first base assumption, and the most conservative one, invalidated, the next assumption is the consideration of two possible activated fasteners for shear force (Fig.3.8). With two activated fasteners, the equilibrium of the structure can be reached. The assumption of two activated fasteners is feasible, from an equilibrium perspective, but it also has to be feasible in reality. These two activated fasteners have to support the whole load of the structure until the failure. If for all cases, when initially two fasteners are bearing shear force, after applying load, a third fastener also get in contact with the base plate and supports shear force, the assumption will not be relevant anymore.

For threaded studs of 10 mm diameter, the standard maximum diameter of the base plate's hole is 18 mm (Fig. 3.9). Considering the Gaussian distribution theory, the highest probability for the position of the fasteners is in the middle of the hole. This average scenario would bring a gap of 4 mm between the edge of the base plate and the fastener, in all directions.

For the same scenario shown in Fig.3.8, with the two top fasteners activated, the required load to achieve a displacement of 4 mm, according to a extrapolation of the elastic function presented in Fig.3.5, would be around 80 kN, which is much higher than the resistance of this structure.

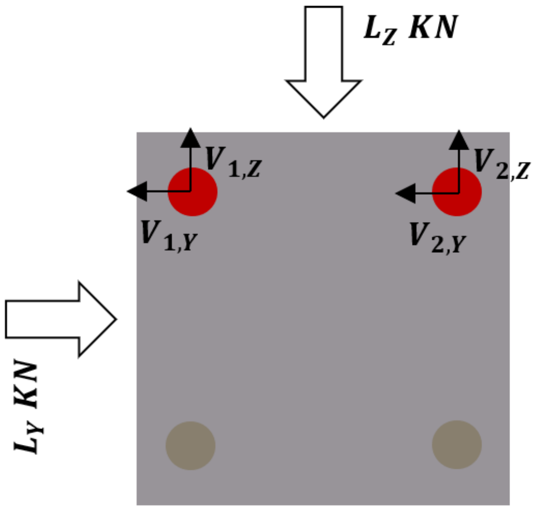


Fig.3.8 – Static base plate with four holes and two fasteners activated.

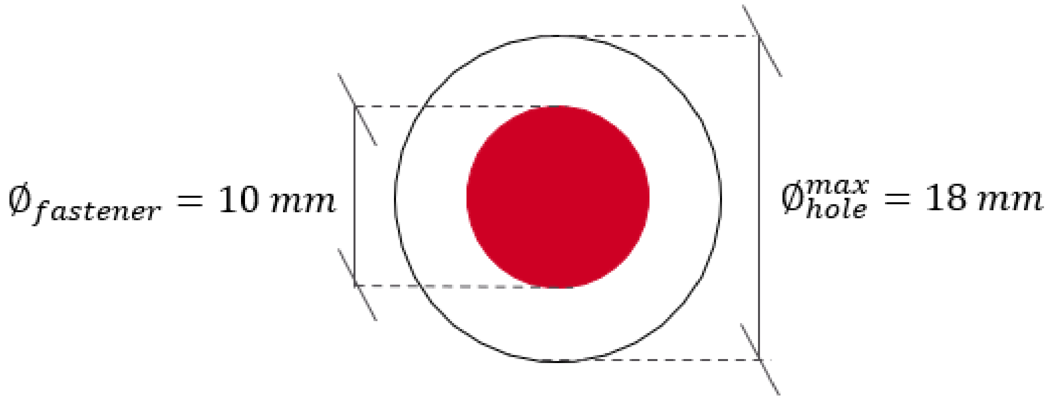


Fig.3.9 – Common configuration of a rounded hole of a base plate, with a fastener inserted.

3.4. CALCULATION MODEL FOR SHEAR FORCE

3.4.1. OVERVIEW

The software Profis MSE considers two main loads as being capable to transmit shear forces on the fasteners:

- Shear load (Y and Z axis);
- Torsion moments (X axis).

The next sub-chapters are dedicated to explaining how the loads results into shear forces on the fasteners and how this calculation is developed under different boundary conditions.

3.4.2. SHEAR LOAD

As previously mentioned, when applying a shear load in the structure, in one or two directions, this load will cause a tendency of translational movement on the base plate, as the dashed line shows in Fig. 3.10. The fasteners are the ones responsible to prevent this displacement as much as possible, by bearing the shear load. The load is then distributed between the activated fasteners (n is the number of activated fasteners), according to the static equilibrium law presented in the equations (3.1) and (3.2):

$$\sum Load_Z = 0 \rightarrow F_Z = \sum_{i=1}^{n} V_{i,Z} \tag{3.1}$$

$$\sum Load_Y = 0 \rightarrow F_Y = \sum_{i=1}^{n} V_{i,Y} \tag{3.2}$$

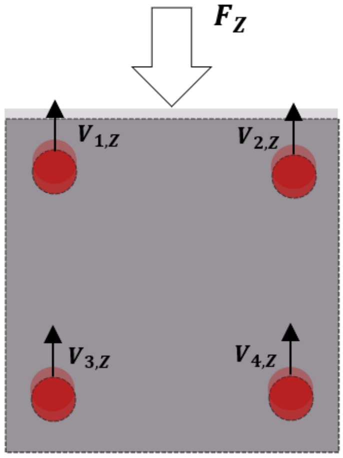


Fig.3.10 – Tendency of displacement of the base plate, due to shear load application.

3.4.3. Torsion moment

Under a similar concept, when applying a torsion moment in the structure, the load will cause a tendency of rotation on the base plate, as the dashed line shown in the Fig. 3.11. Again, the fasteners are responsible to avoid this rotation. The torsion moment is then transmitted as shear force to the fastener, as the fasteners are not able to bear moment in the Profis MSE software, and distributed between the activated fasteners, according to the level arm (r_i) from the support group centroid to the centre axis of the respective fasteners and the static law (equation 3.3).

The centroid of an area, according to Hibbeler (2003) refers to the point that defines the geometric centre of the area, for any arbitrary shape. For this work, the term support group centroid (SGC) will be the one used to refer to the point which defines the centre of the fasteners' area, which can be calculated according to the equations (3.4) and (3.5). The distribution of the amount of moment supported by each fasteners follows the rule in the equation (3.6), where the greatness of the level arm of the respective fastener is the main factor responsible for the moment distribution.

The consideration of torsion moment is essential to the development of the new calculation methodology, not only due to its role of contributing as a load to be transmitted into force on the fasteners, but also to cover any eccentricity that might exist between the shear loads line of application and the support group centroid of the structure.

From now on, the shear loads will be considered applied towards the support group centroid and any eccentricity will be considered as an additional torsion moment.

$$\sum Moment_X = 0 \rightarrow M_X = \sum_{i=1}^{n} V_i \cdot r_i \tag{3.3}$$

$$\bar{y} = \frac{\int_A y \, dA}{\int_A dA} \tag{3.4}$$

$$\bar{z} = \frac{\int_A z\, dA}{\int_A dA} \tag{3.5}$$

$$M_{i,X} = \frac{M_X \cdot r_i}{\sum_{i=1}^{n} r} \tag{3.6}$$

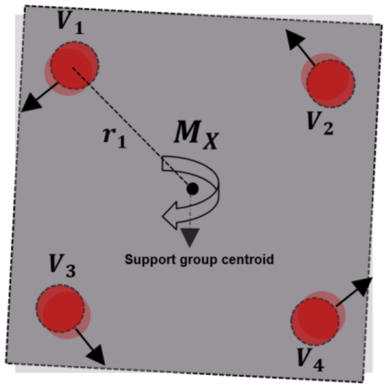


Fig.3.11 – Tendency of rotation of the base plate, due to torsion moment application.

3.5. Definition of case study

3.5.1. General

A methodology of an intensive analysis of an individual unit, under different parameters and boundary conditions, which provides a hypothesis that can be tested systematically and validated, is a crucial step for the development of the work (Denzin and Lincoln 2011). The main purpose for the definition of the case study in this work is to understand how the distribution of shear force among the fasteners under different boundary conditions is done. Firstly, it was decided to select the relevant criteria, which were:

- Number of holes;
- Shape of holes;
- Shape of Typical;
- Relation between forces applied to the structure.

And define a minimum number of case studies, which would allow to understand the relevance of each of the mentioned criteria. Therefore, a first (and standard) case study was chosen (Fig 3.12) and was used a base for the definition of the other cases. For the first case study, as for the next ones, it was assumed the same geometry for the current base plates available in the Hilti's calculation software. As shown in Fig. 3.12, the first standard case is a symmetric square. Changing one parameter of the base case study would allow the understanding of the influence of this parameter on the work, and following this concept the other case studies were defined (Table 3.2) accordingly:

- **Case 1:** Standard and first case, used as a base for the development of all the others, with a relation of 30% between the forces (as suggested by the company).
- **Case 2 and 3:** Investigate changes related to the different numbers of holes among the base plates.
- **Case 4 and 5:** Investigate changes when considering force in only one direction;

- **Case 6:** Investigate changes related to the different shapes of the holes;
- **Case 7 and 8:** Investigate changes related to the different types of Typicals.;
- **Case 9:** Investigate the influence of the torsion moment.

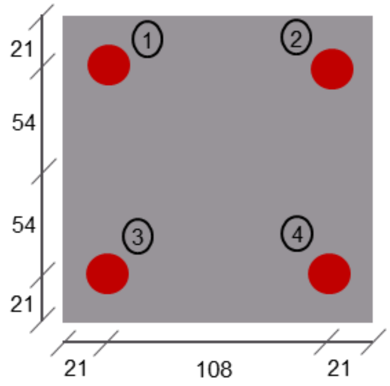


Fig.3.12 – Configuration of the first case study (dimension in mm).

Tab.3.2 – Information of all cases study

Case Study no.	1	2	3	4	5	6	7	8	9
Number of holes	**4**	2	6	4	4	4	4	4	4
Shape of holes	**Circular**	Circular	Circular	Circular	Circular	Slotted	Circular	Circular	Circular
Shape of typical	**Cantilever**	Cantilever	Cantilever	Cantilever	Cantilever	Cantilever	Trapeze	L-Frame	Cantilever
Relation between forces	$\boldsymbol{L_z = 1.0\ kN}$ $\boldsymbol{L_Y = 0.3\ kN}$	$L_z = 1.0\ kN$ $L_Y = 0.3\ kN$	$L_z = 1.0\ kN$ $L_Y = 0.3\ kN$	$L_z = 1.0\ kN$	$L_Y = 0.3\ kN$	$L_z = 1.0\ kN$ $L_Y = 0.3\ kN$	$L_z = 1.0\ kN$ $L_Y = 0.3\ kN$	$L_z = 1.0\ kN$ $L_Y = 0.3\ kN$	$M_x = 1.0\ kNm$

3.5.2. Analysis of sub-cases

As mentioned in the previous chapters, the base assumption of this investigation consists in considering only two activated fasteners between all fasteners on the base plate.

Having this concept as a base, sub-cases were created changing the two-fastener considered as activated between them, with the purpose of investigating the worst-case scenario. As it is not possible to point out which are the fasteners with a proper contact on the base plate (and able to bear shear force) in all installations, it was decided to calculate the distribution of force in all possible scenarios. In the Fig.3.13, it is shown the sub-cases for the first case study (Fig.3.12).

The critical sub-cases are the ones that generate the greatest force on the fasteners, leading to, when considering only shear force, the highest value of utilization of the fasteners. The shear force in all the active fasteners was calculated for the mentioned loads and, in bold text in the Table 3.3, it is also possible to identify which are the active fasteners for each sub-case and the shear force for these respective fasteners, according to the static equilibrium laws and the information provided for this first case study.

There is one relevant factor, that brings a sub-case to a critical situation, when comparing to the even shear force distribution: the new position of the support group centroid (Fig.3.14).

When considering only two activated fasteners for shear force, only these two fasteners are now contributing to the calculation of the new support group centroid.

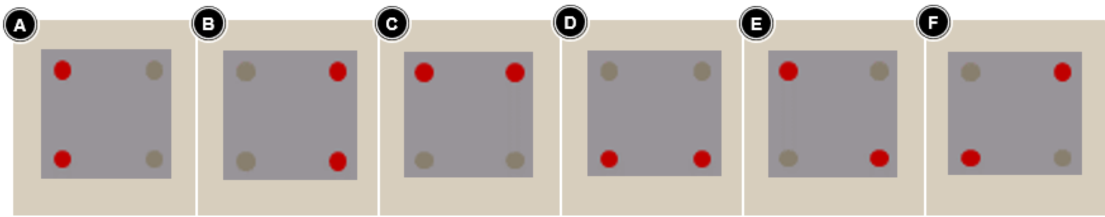
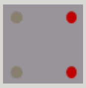
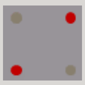


Fig.3.13 – Sub-cases model for the first case study.

Tab.3.3 – Shear force calculation for the sub-cases of the first case study.

			Force [kN]		
			Vy	**Vz**	**Vres**
Sub-case A		**Fastener 1**	0.650	0.500	0.820
		Fastener 2			
		Fastener 3	-0.350	0.500	0.610
		Fastener 4			
Sub-case B		Fastener 1			
		Fastener 2	-0.350	0.500	0.610
		Fastener 3			
		Fastener 4	0.650	0.500	0.820
Sub-case C		**Fastener 1**	0.150	0.650	0.667
		Fastener 2	0.150	0.350	0.381
		Fastener 3			
		Fastener 4			
Sub-case D		Fastener 1			
		Fastener 2			
		Fastener 3	0.150	0.350	0.381
		Fastener 4	0.150	0.650	0.667
Sub-case E		**Fastener 1**	0.150	0.500	0.522
		Fastener 2			
		Fastener 3			
		Fastener 4	0.150	0.500	0.522
Sub-case F		Fastener 1			
		Fastener 2	0.150	0.500	0.522
		Fastener 3	0.150	0.500	0.522
		Fastener 4			

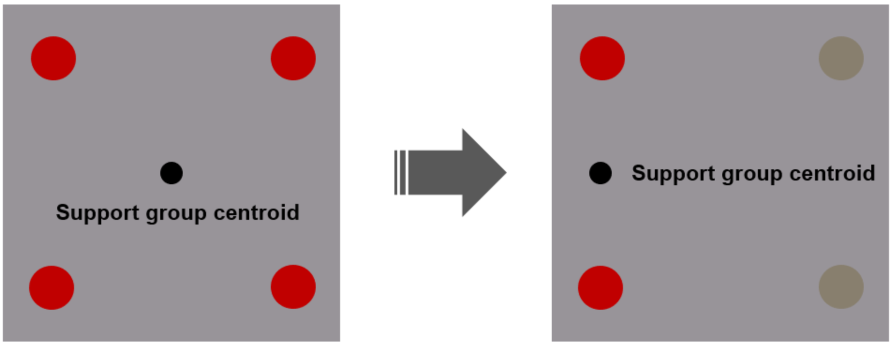


Fig.3.14 – Support group centroid on different configurations.

The change of the position of the fastener's centroid has two main contributions to the new calculation of the shear force on the fasteners:

- The greater the displacement from the initial position to the final position of the centroid, the greater will be the moment due to the eccentricity of the initial position of the load and the position of the new fastener's centroid. Consequently, the greater will be the force on the fasteners to bear this additional moment;
- The smaller the distance between the position of the new support group centroid to the centre axis of the fasteners, the smaller will be the level arm considered to calculate the force on the fasteners due to the moment. Consequently, the greater will also be the force on the fastener.

This analysis is crucial to understanding the distribution of forces when considering two fasteners capable of bearing shear force. It is interesting to notice on the critical sub-case, depending on the total number of fasteners and the distance between their centre of gravity, the emergence of a tendency of rotation on the base plate, due to an eccentricity between the line of the load and the support group centroid. As result, another component of the force on the fastener also emerges, to bear the moment on x axis.

As the component of the force on the fastener in the same direction of the load is half of the load for all the sub-cases, is important to consider that the sub-cases which lead to the highest eccentricity, consequently the highest force on the opposite direction of the load, are the critical ones.

As the new methodology must cover all the possible scenarios, the critical sub-case is from now on the one to be considered to analyse the case study under all the parameters previously mentioned.

3.5.3. Parametrization

Analysis based on generical parameters brings a clear and absolute overview of the influence of this parament for the case study. The modelling of the case, where the side information is continuous in the form of a context parameter, brings accuracy to the observation (Gupta and Barbu 2018).

Implementing a new methodology of calculation in software, requires not only covering all the current structures already available in the system, but also the possibly new ones that might come in the future. After analysing all the case studies, was clear that they covered most of the structures available in the Profis MSE software. However, some parameters, for example the position of the holes, which relevance for the redistribution of shear force in this investigation is now evident, were not covered by the initial case studies. Therefore, after bringing up this topic, was clear that another requirement had emerged:

the need to parametrize the criteria and establish a global case study. This investigation was then based on an adoption of a generical (and realistic) case study, in which boundary conditions are parameterized, and the main goal is to cover all main relevant criteria for the current structures and for the ones that might come in the future.

After analysing the current brackets available in the Hilti calculation software and the research for the next ones, some global patterns were identified. These patterns were deep studied for the creation of the case study. The configuration of all the base plates is consistent with the following rules:

- The shape of the base plates has a rectangular format;
- The holes are located nearby the edge of the base plates and;
- To guarantee a stable configuration of the structure and avoid huge force due to eccentricity and asymmetry, the holes are always distributed in pairs, located on opposite edges (Fig.3.15).

These rules and the criteria mentioned previously were the base for the construction of a generical case study model. As the shape of the base plates is rectangular, they can only vary according to the Fig.3.16. All this information allowed the creation of the model shown in the Fig.3.17. The case model represented in this figure, illustrates a corner of a generical base plate, which can have any rectangular geometry (according to the Fig.3.16), with all the loads, two shear load, in Z and Y ($L_Z$and L_Y) direction, and a torsion moment in X direction (M_X), applied towards the support group centroid, as previously defined at the beginning of this chapter. The centre axis of the fastener can be placed anywhere along the edges of the base plate, from the corner until the line of both loads (coordinates y and z). The dimension of the base plate assumes the nomenclature D_Z and D_Y, for the axis z and y respectively.

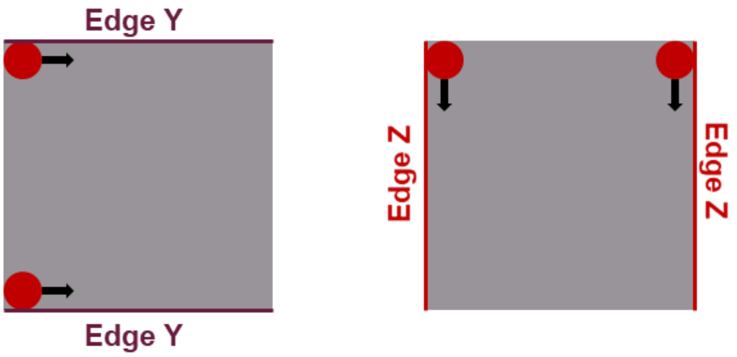


Fig.3.15 – Fasteners distributed in pairs along the edges of the base plate.

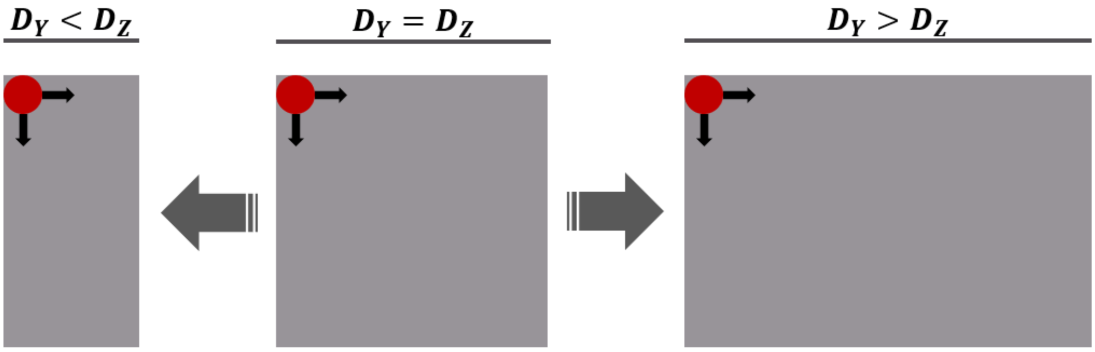


Fig.3.16 – Possible geometry configuration of the base plate.

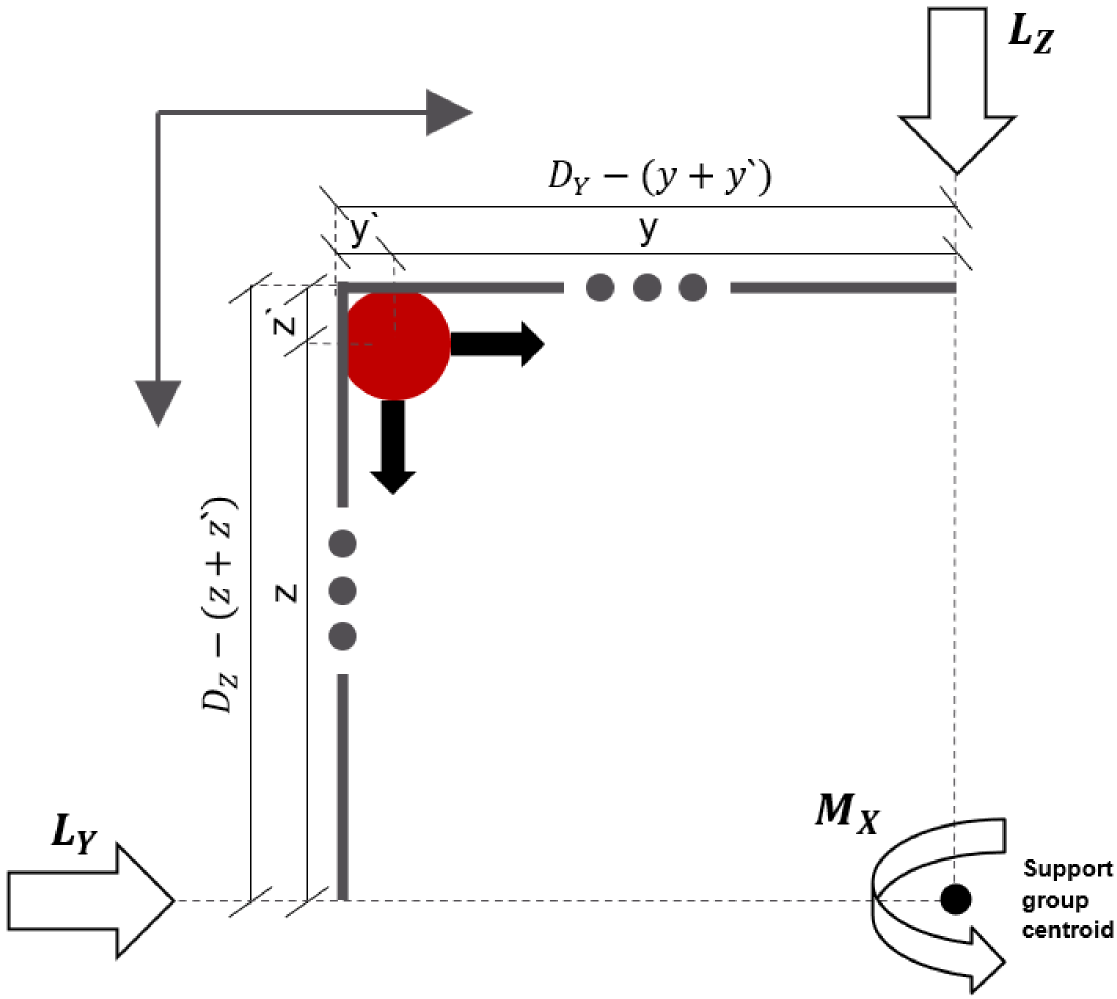


Fig.3.17 – Model of the parametrized case study.

3.6. SHEAR FORCE ANALYSIS UNDER DIFFERENT BOUNDARY CONDITIONS

As discussed in the previous sub-chapter, when considering only two activated fasteners, the redistribution of force on the fasteners might lead to the following configuration, as shown in the Fig.3.18.

Currently, the calculation software Profis MSE does not have this assumption, but instead it considers that all fasteners are able to have proper contact with the base plate and receive shear force. The force is equally distributed between all the fasteners and the results are more conservative, as suggested in the comparison shown in the Fig.3.19.

The difference between both cases emphasizes again how is relevant the study and, later, the implementation of a new calculation methodology for shear force distribution between the fasteners. As previously investigated at the beginning of the chapter, assuming a scenario where only two fasteners are bearing all the shear force is realistic.

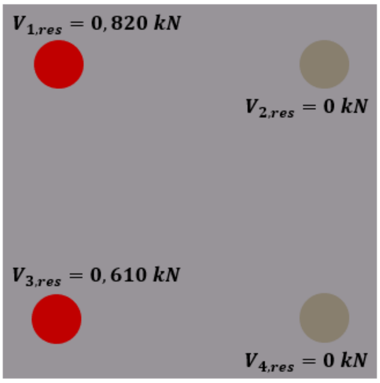


Fig.3.18 – Shear force result per fastener of the worst sub-case.

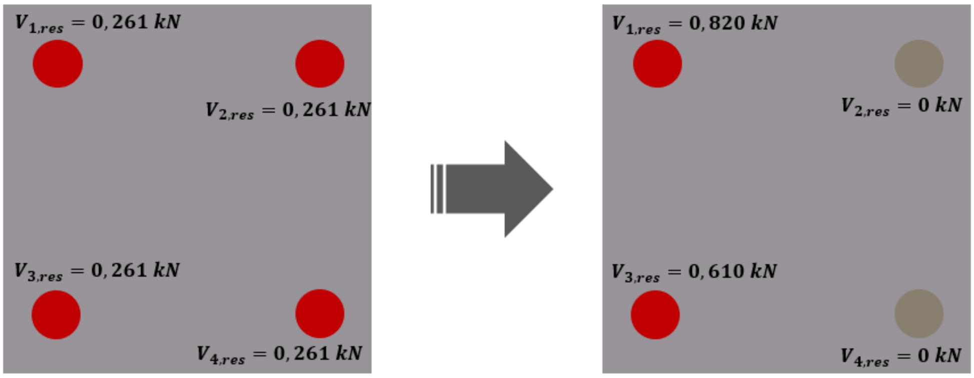


Fig.3.19 – Shear force result per fastener for the current methodology on the left, and for the proposed one on the right.

4

PROPOSAL OF A NEW CALCULATION METHODOLOGY

4.1. GENERAL

As discussed in the previous chapters, the current methodology adopted in Profis MSE may underestimate the forces acting on the fasteners when worst case contact conditions occur. This is especially relevant for stiff fasteners. In this chapter will be presented the formulation to calculate the force, based on the assumption of two activated fasteners, as well as the influence of the tension force and how the software will use this knowledge to proceed with the new methodology. Therefore, the methodology will be detailed, according to the following steps:

- Shear force calculation;
- Identification of the critical fasteners;
- Shift of forces.

4.2. SHEAR FORCE CALCULATION

The bases for the formulation of the new methodology is the analysis of the case studies. The analysis was first made with the initial case studies, and for the explained purpose the initial (and standard) case study, shown in Fig.3.12, will be used to define each step of the formulation. Then, for each same step, the formulation will be adapted based on the parametrized case study (Fig.3.17), aiming at a general and global methodology.

The steps to define the formulation were based on all the criteria that need to be covered, according to:

i. Initial approach;
ii. Geometric dimensions;
iii. Relation between loads;
iv. Load deviation;
v. Torsion moment;
vi. Shape of the holes;
vii. Fasteners without eccentricity.

4.2.1. Initial approach

The first step to initiate the definition of the formulation was to identify and deep analyze the range of the force on the fasteners under an unit load, for the simple and standard configuration. Using the initial case study, under a load of 1 kN in z direction, and considering the maximum force on the fasteners activated, for all possible sub-cases, the following results are shown in Fig. 4.1.

For this standard case study, when applying an unit load of 1 kN, the range of force in the fasteners goes from a minimum resultant, when both components assume no force, to a maximum resultant when both components assume the maximum value in modulus of half of the force. It is also important to notice that some fasteners, namely the fasteners 1 and 4, only assume positive values, from 0 to 0.5, in both components and the other two, namely the fasteners 2 and 3, have one component assuming the same positive values and the other negative values from – 0.5 to 0. For this case, with an unit load in z direction, the negative component is in y direction. The reason for a component with a negative sign is easily identified after the analysis of the tendency of movement of the base plate in one of the possible sub-cases, as shown in Fig. 4.2.

As the concept of the Profis MSE software is to support the engineer's community to design structures with the available portfolio, the relevant information for the development of the methodology is only the maximum force that can be assumed on a fastener, for all possible combinations of two activated fasteners (sub-cases).

Based on the example described, the formulation starts to be built. Consider only two activated fasteners, the resultant shear force on a fastener (Table 4.1) of a square base plate with four fasteners, under an unit load in only one direction (z axis for this case), no torsion moment applied and rounded holes, has the maximum value of $\sqrt{2}\ \cdot 0{,}5\ kN$. The $0{,}5\ kN$ can also be considered as half of the load in z direction applied, bringing the equation (4.1).

$$V_{res} = \sqrt{2}\ \cdot \frac{L_Z}{2} \tag{4.1}$$

As there are two activated fasteners, and for all of them one component always assumes positive value and the other may assume either a positive or negative value, the previous equation can be adjusted to the equation (4.2).

$$V_{1\ and\ 2,res} = \sqrt{\left(\frac{L_Z}{2}\right)^2 + \left(\pm\frac{L_Z}{2}\right)^2} = \frac{L_Z}{2} \cdot \sqrt{(1)^2 + (\pm 1)^2} \tag{4.2}$$

The equation above was the bases to build the methodology. This initial approach will provide both components (values inside the brackets) and the resultant force of the two activated fasteners, for the posterior design of the whole structure in Profis MSE software, but this time considering the lack of ductility of some fasteners, in other words, a more realistic result.

For the parametrized case study, the formulation embodies the same configuration as the standard one. Therefore, no changes are made for this first step. For the following criteria, the first analysis will be made with the standard and initial case study and afterwards incorporated for the general and parametrized one, when relevant.

Table 4.1 – Minimum and maximum shear force resultant for the standard case study, under an unit load.

	Resultant shear force on the activated fastener
Minimum	$V_{res} = 0\ kN = 0\ \cdot 0{,}5\ kN$
Maximum	$V_{res} = 0{,}707\ kN = \sqrt{2}\ \cdot 0{,}5\ kN$

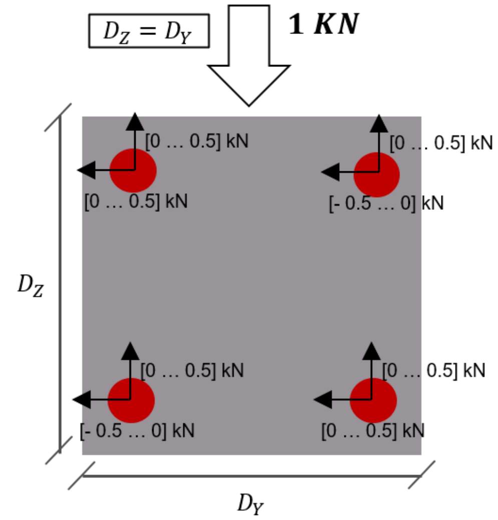


Fig. 4.1 – Range of forces in the all the fasteners, under an unit load in z direction.

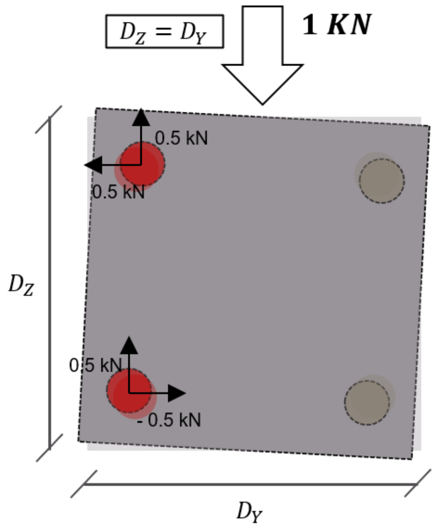


Fig. 4.2 – Tendency of movement of the base plate, shows the reaction force component in y direction assuming different directions.

4.2.2. GEOMETRIC DIMENSIONS

The base plates in Profis MSE do not only assume symmetric configurations and the distances between the centre axis of the fasteners in y and z directions and the edges of the base plate are not always the same. Therefore, the formulation that was defined in the software needs to incorporate this criterion and be valid for all rectangular geometry of the base plate and all distances between the centre axis of the fasteners.

Following the same analysis done in the previous sub-chapter, the range of force was calculated for the same parameters, but changing the dimensions of the base plate. Having the relation between the distances as the base, Fig. 4.3 shows the influence of the parameters for the calculation of the shear force. When the relation between the distances (D_Y/D_Z) has a ratio of 2, the range of the force on the fasteners after analysing all possible sub-cases for only one component has twice the size. With a similar concept, when the ratio goes to 0.5, the range of the force decreases by half. The influence of the ratio per load is presented in the Fig.4.4.

Notice that, with this case study configuration of an unit load in only one direction, the influence of the variation of the dimensions is only relevant for one component of the force, the one perpendicular to the direction of the load. For the sub-cases where the support group centroid of the activated fasteners is already in the line of the load application (Fig. 4.5), there is no eccentricity and, consequently, additional moment to be considered. As mentioned at the beginning of the work, the loads are always applied toward the support group centroid, therefore, for the other sub-cases (Fig. 4.6), an additional moment will occur due to the eccentricity, and the component of the force responsible to bear this additional load is only the one perpendicular to the direction of the force, as shown the Fig. 4.7, when comparing the initial case study with two different ratios of dimensions.

A new factor will be incorporated in the formulation, which considers the mentioned ratio of the dimensions of the base plate. The methodology changes according to the equation (4.3).

$$V_{1\ and\ 2,res} = \sqrt{\left(\frac{L_Z}{2}\right)^2 + \left(\pm\beta \cdot \frac{L_Z}{2}\right)^2} = \frac{L_Z}{2} \cdot \sqrt{1^2 + (\pm\beta)^2} \tag{4.3}$$

For the initial case, the dimensions ratio factor β was the relation between the distances of the base plate (equation 4.4). But, as not all the base plates have the same distance between their edges and the centre axis of the fasteners, the formulation will be adapted for the general case study. The coefficient assumes the following relation:

$$\beta = \frac{y}{LA_Z} \tag{4.4}$$

Where y is the greatest component of distance between the centre axis of the fastener and the line of the load application, in y direction (Fig.3.17). And LA_Z is the smallest level arm between the two activated fasteners, in z direction.

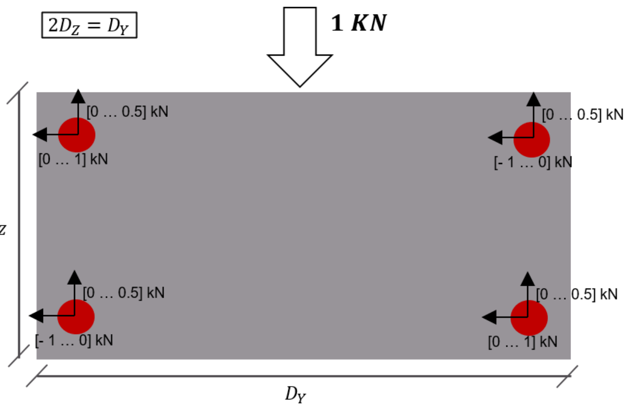


Fig.4.3 – Shear force result per fastener under different dimensions ratio.

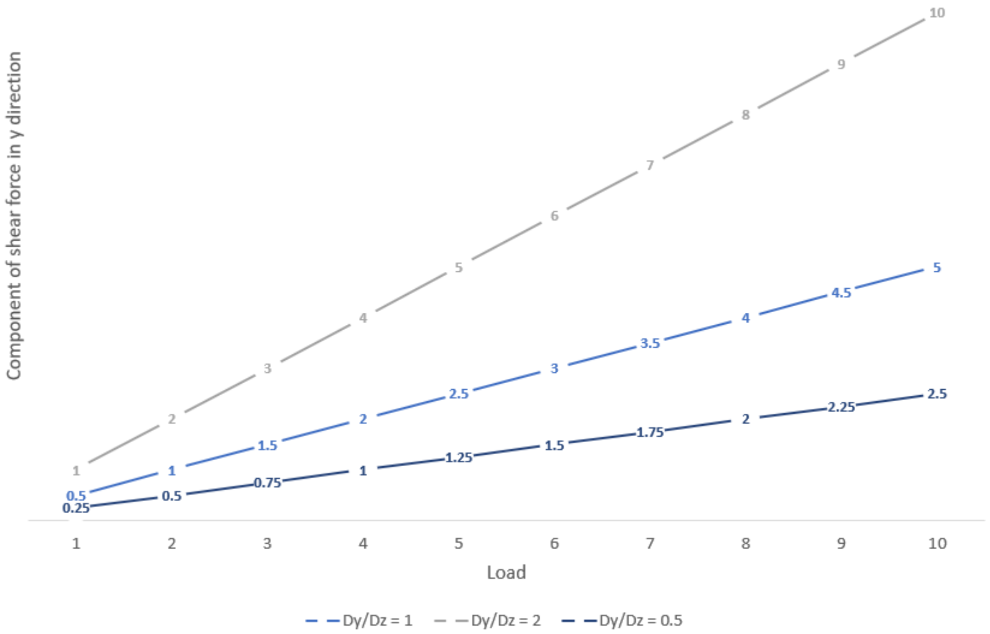


Fig. 4.4 – Dimensions ratio influence for the shear force calculation.

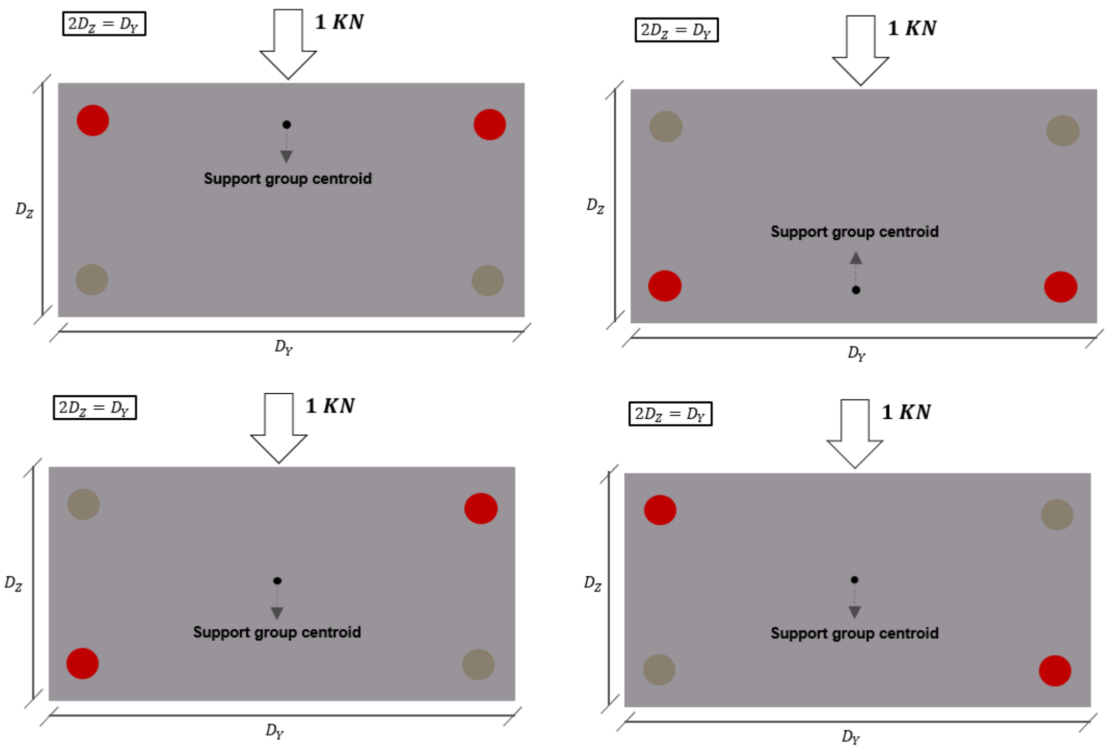


Fig. 4.5 – Sub-cases with the support group centroid in line with the load application.

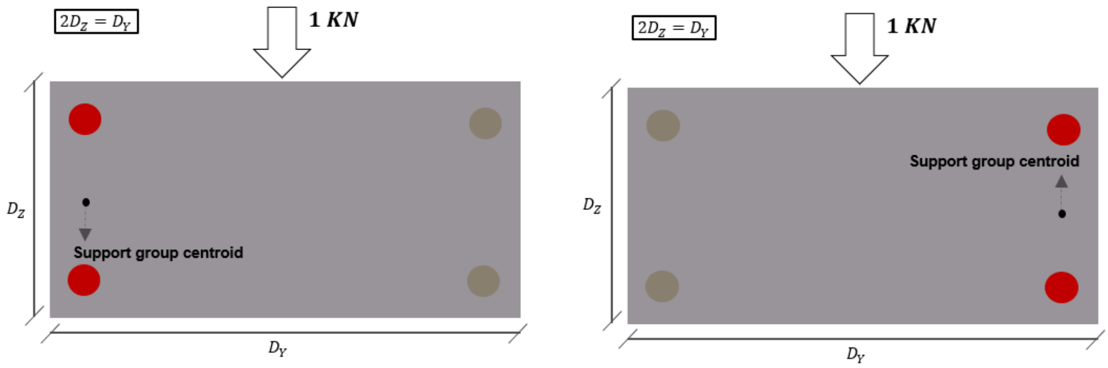


Fig. 4.6 – Sub-cases with the support group centroid eccentric with the load application.

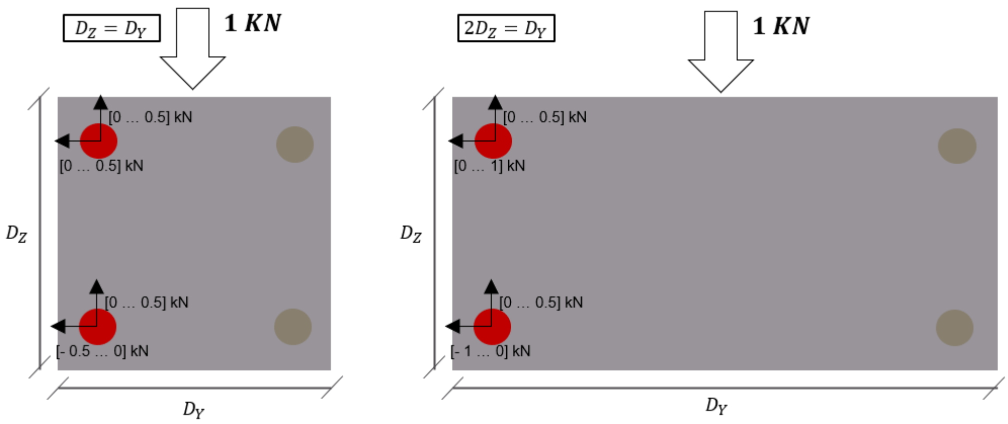


Fig. 4.7 – Comparison of the initial analysis of the standard case study, under different dimensions ratio.

4.2.3. Relation between loads

As mentioned at the beginning of the fourth chapter, not only the load in one direction will be responsible to transmit shear forces to the fasteners, but also the load in both directions and the torsion moment. Therefore, these are the subjects for the next steps.

As shown in the previous calculations, the worst sub-cases are those in which an additional moment emerges, due to the eccentricity between the support group centroid and the line of the load application. In the case of two loads applied, in y and z directions, the critical results would eventually come from a configuration where both loads are eccentric. But as shown in Fig. 4.8, the activated fasteners, for a critical sub-case under a load applied in z direction, are not the same when the load is applied in y direction.

Define which fasteners have a proper contact with the base plate is not one of the targets of this research, but to analyse the possible realistic scenarios and propose a formulation, which covers all of them. For the case with load applied in both directions, would not be realistic to consider the fasteners 1 and 3 activated for the calculation of the force due to the load in z direction, and the fasteners 1 and 2 activated for the same purpose, but due to the load in y direction. Both causes are feasible, when analysed separately, but not a merge of them. Therefore, for the development of the formulation, either the centroid of the activated fasteners:

- Will be eccentric in relation to the load in z direction, and create an additional moment that will be supported by the component of the force in y direction or;
- Will be eccentric in relation to the load in y direction, and create an additional moment that will be supported by the component of the force in z direction or;
- Will have no eccentric in relation to both loads, and no additional moment will occur.

As the case where both loads will be eccentric to the centroid will not be considered in this work, the greatest force will be the one destinated to be eccentric and create the additional moment. This approach brings the realistic worst scenario and also covers the case where the smallest force is the one eccentric. For that, a new factor will be incorporated, the load ratio factor. The new factor (and also the dimension ratio factor) will assume different values, according to the relation of the loads presented in the equations (4.5), (4.6) and (4.7).

$$L_Z \geq L_Y \;\rightarrow\; L = L_Z \;\; ; \; \beta \; = \frac{y}{LA_Z} \;\; ; \;\; \Delta = \frac{L_Y}{L_Z} \tag{4.5}$$

$$L_Z < L_Y \;\rightarrow\; L = L_Y \;\; ; \;\; \beta \; = \frac{z}{LA_Y} \;\; ; \;\; \Delta = \frac{L_Z}{L_Y} \tag{4.6}$$

$$V_{1\ and\ 2,res} = \sqrt{\left[\frac{L}{2}\right]^2 + \left[(\pm\beta + \Delta)\cdot\frac{L}{2}\right]^2} = \frac{L}{2}\cdot\sqrt{1^2 + (\pm\beta + \Delta)^2} \tag{4.7}$$

Notice that, when the load in z and in y directions are equal, the formulation will run according to the case when the load in z direction is the greatest and the load ratio factor will assume the unit value. The formulation, as it is right now, can also be applied for the parametrized case study and, therefore, no changes are needed for this step.

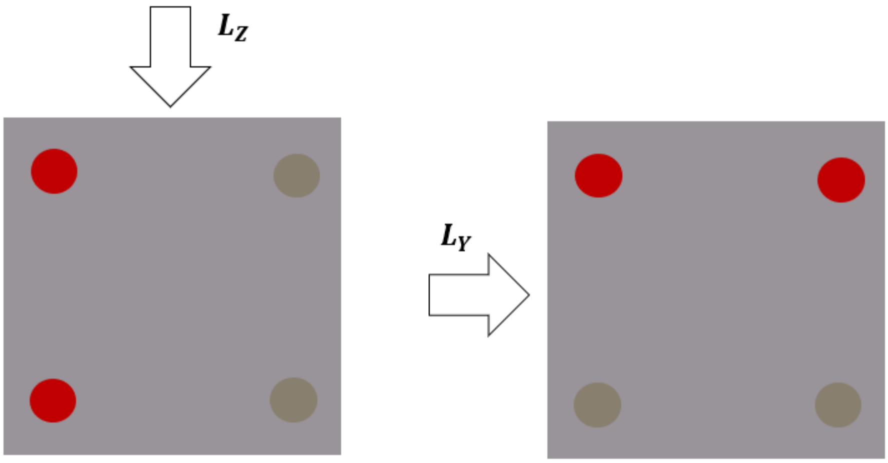


Fig. 4.8 – Comparison of the critical sub-case when the load is applied in z and y direction.

4.2.4. Load deviation

There is some cases, for example where the cantilever beam has a braced (Fig.2.5), where currently the total load applied in a structure in Profis MSE is not integrally distributed to the fasteners on the base plate of the cantilever beam, due to a deviation of the load for other support (the base plate of the braced structure, for the mentioned case). With the purpose to keep the current general calculation of the structure, and modify only the distribution of shear force from the base plate to the fasteners, the formulation will be adapted according to the equations (4.8) and (4.9).

$$\sum V_Z \geq \sum V_Y \;\rightarrow\; L = \sum V_Z \;\; ; \; \beta \; = \frac{y}{LA_Z} \;\; ; \;\; \Delta = \frac{\sum V_Y}{\sum V_Z} \tag{4.8}$$

$$\sum V_Z < \sum V_Y \;\rightarrow\; L = \sum V_Y \;\; ; \;\; \beta \; = \frac{z}{LA_Y} \;\; ; \;\; \Delta = \frac{\sum V_Z}{\sum V_Y} \tag{4.9}$$

Where $\sum V_Z$ is the sum of the shear forces on the fasteners in z direction and $\sum V_Y$ in y direction, calculated with the current methodology. The calculation routine of the software will first sum the shear force in all the fasteners in one direction and compare it to the other. This concept allows the new methodology to run the distribution of shear forces from the base plate to the activated fasteners, without changing the previous step done by RSTAB.

4.2.5. Torsion moment

With the formulation developed until that point, any additional moment created due to the eccentricity between the centroid and the load is covered. The methodology to incorporate the torsion moment as a load follows similar steps, but is adapted to the calculation format of the tension moment in Profis MSE, as described in the sub-chapter 3.4.3.

When analyzing the standard case, under a torsion moment applied in the support group centroid (Fig. 4.9), the main differences for the current calculation in the software with all fasteners activated to the new proposal with only two activated fasteners are:

- The moment will be supported by only two fasteners, according to the proportion shown in the equation (3.6);
- The direction of the force vectors of the fasteners will differ from case to case, according to the new position of the support group centroid and;
- Due to the change in the position of the centroid, a new level arm will be considered for the calculation of the shear force in the fasteners.

For the formulation, the direction of the resultant component under torsion moment will not be properly considered. The objective will be first to understand the force distribution when considering all the fasteners, and then provide a similar solution under the boundary conditions of the base assumptions of this work (two activated fasteners), adjusted by correction factors.

The first step is to separate the load coming from the torsion moment to the load coming from the loads in z and y directions (plus the additional moment that occurs when there is eccentricity). Therefore, the calculation routine will change according to the equations (4.10), (4.11) and (4.12).

For the load:

$$\sum V_{Z,Load} \geq \sum V_{Y,Load} \rightarrow L_{Load} = \sum V_{Z,Load} \quad ; \beta = \frac{y}{LA_Z} \quad ; \Delta = \frac{\sum V_{Y,Load}}{\sum V_{Z,Load}} \tag{4.10}$$

$$\sum V_{Z,Load} < \sum V_{Y,Load} \rightarrow L_{Load} = \sum V_{Y,Load} \quad ; \beta = \frac{z}{LA_Y} \quad ; \Delta = \frac{\sum V_{Z,Load}}{\sum V_{Y,Load}} \tag{4.11}$$

And for the torsion moment:

$$L_{Moment} = \sum V_{res,Moment} \tag{4.12}$$

In the current methodology, the torsion moment is supported by all the fasteners, according to the distance between the support group centroid and the centre axis of each fastener (equation 3.3). For the development of the formulation, the next step will be to calculate an average for the distance $\bar{r}$, which provides the total torsion moment applied in the structure when multiplied by the sum of the shear force result, due only to the torsion moment (equation 4.13).

$$M_X = \sum V_{res,Moment} \cdot \bar{r} \tag{4.13}$$

This simplified proposal would allow to cover the torsion moment in the formulation, by distributing half of the load (L_{Moment}) for each activated fasteners and correct it by another coefficient, the level arm factor, for both directions. The support group centroid will change the position, as only two fasteners are considered activated now. The critical new position for the centroid is the one between both fasteners, which are the closest to each other, which means, have the smallest LA. Therefore, the level arm factor will relate the initial average distance between centroid and centre axis of the fasteners, with half of the smallest LA possible for each base plate, per coordinate. The equation (4.14) presents the part of the formulation dedicated to the torsion moment. Moreover, the level arm factor assumes the rule described in the equations (4.15) and (4.16).

$$V_{1\ and\ 2,res} = \frac{L_{Moment}}{2} \cdot \sqrt{\left(\frac{\bar{r}}{LA_z/2}\right)^2 + \left(\frac{\bar{r}}{LA_y/2}\right)^2} = \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2} \tag{4.14}$$

$$\omega_y = \frac{\bar{r}}{LA_z/2} \tag{4.15}$$

$$\omega_z = \frac{\bar{r}}{LA_y/2} \tag{4.16}$$

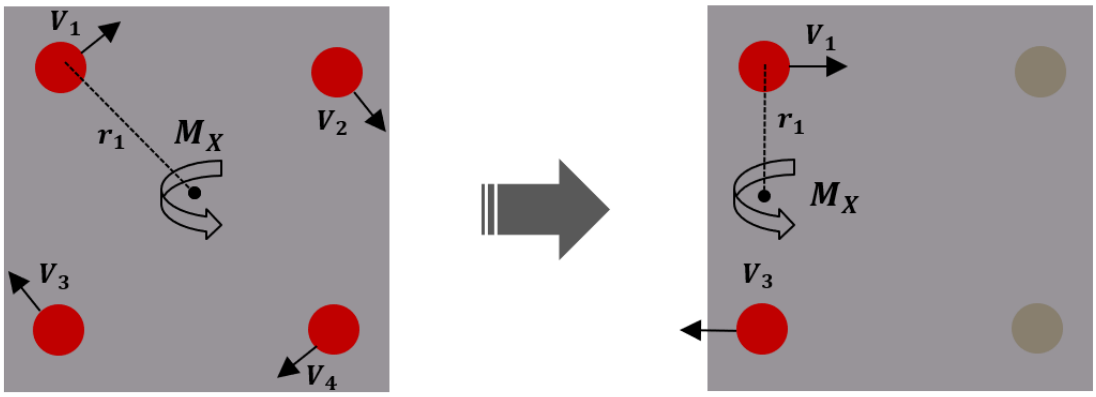


Fig. 4.9 – Torsion moment applied in the centroid under different boundary conditions.

4.2.6. Shape of the holes

The location where the threaded studs are inserted in the base plates can assume two different shapes: rounded and slotted. The slotted holes are winded in one direction, with the main purpose of better assure the contact between the fastener and the edge of the base plate in the opposite direction of the enlargement.

The current calculation methodology for slotted holes is shown in Fig. 4.10. Only the fasteners inserted in a hole, enlarged in the opposite direction of the load, are supporting shear force. Even though these fasteners are not the ones in proper contact with the base plate at the first moment, the increase of the load, and consequently the deformation of the fasteners, would lead to their contact, as the slotted were defined with the concept of guarantee the contact requiring small deformations (and ductility).

Therefore, no new changes will be done to the shear force distribution between the fasteners in the Profis MSE software for base plates with slotted holes and the focus of this proposal new methodology will be the rounded holes.

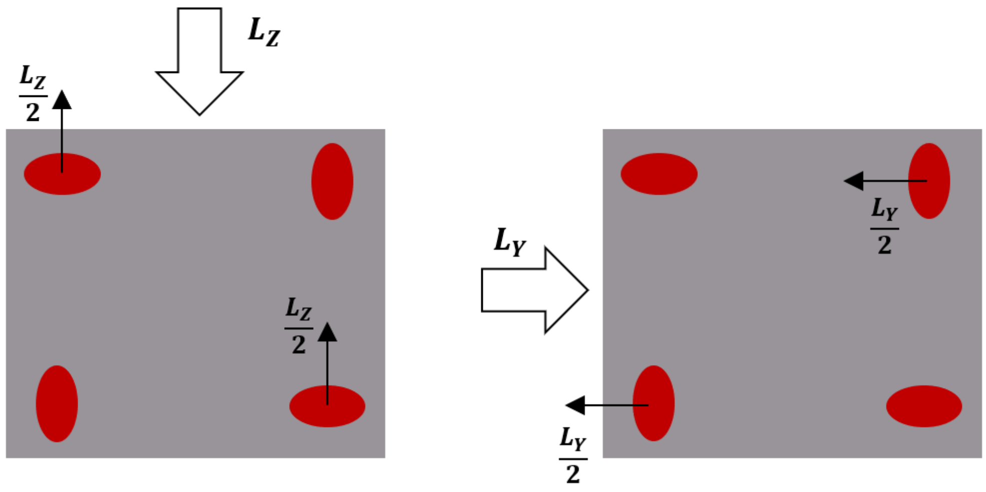


Fig.4.10 – Distribution of shear force for fasteners inserted in slotted holes, under load application in different directions.

4.2.7. Fasteners without eccentricity

Based on the case study described in the Fig.3.17, the position of the fastener can assume two configurations, in the line of the load application and outside the same line. The shear force calculation has differences under these two configurations and, therefore, they will be considered.

When the activated fastener stays in the line of the load application, based on the static equilibrium laws, all the force will be distributed for it. An activated fastener which is not located toward the line of load application, will either only support half of the load applied, or support half of the load and also support the moment due to the eccentricity between the centre axis of the fastener and the line of load application, which for our work will be always considered towards the support group centroid, as previously mentioned.

Therefore, the last coefficient of this chapter is introduced, the eccentricity factor. Responsible to dictate whether the whole load will be distributed to the fastener which is located in the line of the load application, occasion where the coefficient assumes the unit value, or the load will be shared half for each fastener, where the coefficient has the value of 2.

Notice that, when the centre axis of the fasteners is located in the line of the load application, the dimension ratio factor will be null. The relevance of this new factor exists only for the load part of the equation (and not for the moment), therefore the formulation will incorporate as shown in the equation (4.17) and according to the conditions described in the Table 4.2.

$$V_{1\ and\ 2,res} = \frac{L_{Load}}{\gamma} \cdot \sqrt{1^2 + (\pm\beta + \Delta)^2} \tag{4.17}$$

Table 4.2 – Conditions for the eccentricity factor values.

Condition	Factor
When the fastener is in the line of the load application	$\gamma = 1$
When the fastener is not in the line of the load application	$\gamma = 2$

4.3. IDENTIFICATION OF THE CRITICAL FASTENERS

Two fasteners, out of the whole number of fasteners per base plate, will support the whole shear force, which before was evenly distributed for all. The other fasteners, not activated, will then receive no shear force for the software calculation. The next step of the methodology is to identify the critical fasteners.

The critical fasteners are the two fasteners supporting the highest tension force. Part of the calculation routine of the Profis MSE software is to calculate and distribute tension force for all the fasteners. Before starting the part destinated to the new methodology of shear force distribution, the two critical fasteners will be selected. In case the fasteners have the same tension force, the first two fasteners will be the ones selected.

4.4. SHIFT OF FORCES

The last part of the methodology is the shift of forces. After calculating the shear force for the two activated fasteners (equation 4.18) and for the others (equation 4.19).

$$V_{1\ and\ 2,res} = \frac{L_{Load}}{\gamma} \cdot \sqrt{1^2 + (\pm\beta + \Delta)^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2} \tag{4.18}$$

$$V_{others,res} = 0 \tag{4.19}$$

The result shear force for the activated fasteners will be transferred to the critical fasteners and the utilization of all fasteners will be calculated (equation 2.9), without the alpha coefficient group.

4.5. Concluding remarks

The proposed methodology is adapted according to the relation between the sum of shear force in both directions. The general formulation has the framework detailed in the equations (4.10), (4.11), (4.12), (4.20) and (4.21).

$$\sum V_{Z,Load} \geq \sum V_{Y,Load} \rightarrow V_{1\ and\ 2,res} = \frac{L_{Load}}{\gamma} \cdot \sqrt{1^2 + (\pm\beta + \Delta)^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2} \quad (4.20)$$

$$\sum V_{Z,Load} < \sum V_{Y,Load} \rightarrow V_{1\ and\ 2,res} = \frac{L_{Load}}{\gamma} \cdot \sqrt{(\pm\beta + \Delta)^2 + 1^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2} \quad (4.21)$$

Not only the resultant shear force in the activated fasteners is calculated, but also each component of the force. According to the Fig. 4.11, where the formulation assumes the case where the sum of shear force in z direction is equal to or higher than the same sum in y direction, the red text is the y component of the result (inside the first bracket of each square root) and the blue text is the z component (the second bracket).

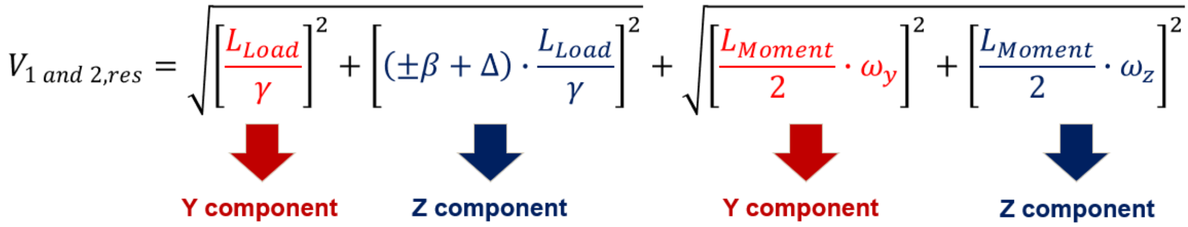


Fig.4.11 – Shear force components description.

5
SOFTWARE IMPLEMENTATION

5.1. GENERAL

The calculation methodology is based on a parametrized formulation to calculate the maximum resultant shear force in any of two fasteners, among all the fasteners installed in the structure. Handing over the technical data and the boundary conditions of the proposed methodology to be implemented in the calculation routine of the Profis MSE software is the last activity of the research. Understanding the standard implementation processes for the mentioned software, together with the effort required for each of them, is an essential activity to better elaborate the possible implementation approaches and their respective advantages and disadvantages, likewise the benefit of each approach versus the effort demanded.

The solution that brings the most accurate result and it covers all the possible cases available in calculation software requires a high amount of effort (labour time, additional code lines in the routine, extra variants and others) to be implemented. Therefore, three additional approaches were defined, to bring the solution developed in this work into Profis MSE calculation routine. All the three additional solutions are based on a similar concept: the development of a reduction factor, called shift of forces factor (α_{sf}), which is responsible to decrease the resistance of all the fasteners, during the utilization procedure (equation 2.9). Similar to the previous group coefficient (α_{group}), the new shift of forces factor differs by following the base assumption described in chapter 3 and trying to keep all the benefits of the methodology developed in chapter 4, but decreasing the effort to be implemented, according to each approach. The scope of this chapter is the detail of the following approaches:

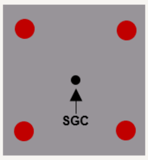
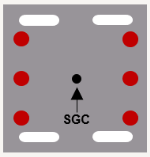
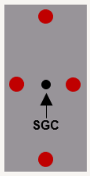
- General function coefficient;
- Specific function coefficient;
- Constant coefficient.

All the three solutions are based on the coefficients detailed in chapter 4. And for the development of the second and the third approaches, the moment part of the equation will be simplified covered by the load ratio factor and all the base plates will be grouped into four categories (Table 5.1):

- **Category 1:** Base plates which have no fastener in the line of load application and more than two fasteners;
- **Category 2:** Base plates which have, in one direction, fasteners in the line of the load application and more than two fasteners;
- **Category 3:** Base plates which have, in both directions, fasteners in the line of the load application;

- **Category 4:** Base plates with two fasteners or less.

Table 5.1 – Base plate models for the four categories.

Categories	**1**	**2**	**3**	**4**
Models				

5.2. General function coefficient

The first approach requires the highest amount of effort to be implemented, among the additional solutions, and is the most complex one. The shift of forces coefficient is based on a relation between the current calculation of the resultant shear force in the fasteners (equation 5.1), where n is the total number of fasteners on the base plate, divide by the proposal new calculation of the resultant shear force developed in this work. In the equation (5.2), is presented the general function coefficient, for the case when the sum of the shear force in the fasteners in z direction is equal or higher than in the y direction.

$$V_{res,current} = \sqrt{\left[\frac{L}{n}\right]^2 + \left[\frac{\Delta \cdot L}{n}\right]^2} \tag{5.1}$$

$$\alpha_{sf} = \frac{\sqrt{\left[\frac{L}{n}\right]^2 + \left[\frac{\Delta \cdot L}{n}\right]^2}}{\frac{L_{Load}}{\gamma} \cdot \sqrt{1^2 + (\pm\beta + \Delta)^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2}} \tag{5.2}$$

5.3. Specific function coefficient

The second approach brings the shift of forces coefficient similar to the previous one, but instead of a generical formulation, each base plate category will have its own function to calculate the factor (equation 5.3).

$$\alpha_{sf,i} = \frac{\sqrt{V_{res,current}}}{\sqrt{V_{res,cat,i}}} \tag{5.3}$$

The new proposal formulation for each of the base plate categories ($V_{res,cat,i}$), is based on the calculation of the resultant shear force in the most loaded fastener, of the most critical sub-case. In the Table 5.2, it is detailed the components of the shear resultant force of the critical fastener in both configurations, the current calculation methodology and the new proposal. The shear resultant function per category, as detailed in the equation (5.4), (5.5), (5.6) and (5.7).

Category 1

$$V_{res,cat,1} = \sqrt{\left[\frac{L}{2}\right]^2 + \left[(\beta + \Delta) \cdot \frac{L}{2}\right]^2} \tag{5.4}$$

Category 2

$$V_{res,cat,2} = \sqrt{\left[\frac{L}{2}\right]^2 + \left[(\beta + 2 \cdot \Delta) \cdot \frac{L}{2}\right]^2} \tag{5.5}$$

Category 3

$$V_{res,cat,3} = \sqrt{L^2} \tag{5.6}$$

Category 4

$$V_{res,cat,4} = \sqrt{\left[\frac{L}{2}\right]^2 + \left[\frac{\Delta \cdot L}{2}\right]^2} \tag{5.7}$$

In the current configuration of the specific function coefficients, the total number of fasteners was standardized, per category, and a simplified formulation was defined (Table 5.3). Notice that, if a base plate can be included in one of the categories, but has a different total number of fasteners compared to the defined one, the simplified formulation should not be used and a new one should be formulated, according to the equation (5.1) and (5.3), and the right total number of fasteners.

Table 5.2 – Components of the shear resultant force of the critical fasteners for the current calculation methodology and the new proposal.

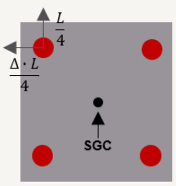
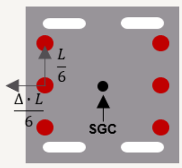
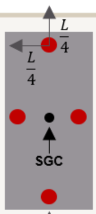
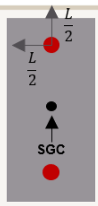
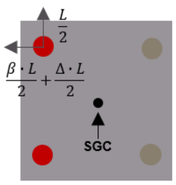
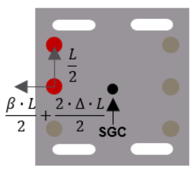
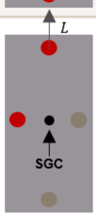
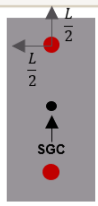
Categories	1	2	3	4
Current calculation				
New proposal				

Table 5.3 – Simplification of the specific function coefficients for all the categories.

Categories	1	2	3	4
Specific function coefficients	$\alpha_{sf,1} = \frac{1}{2}\sqrt{\frac{1+\Delta^2}{1+(\beta+\Delta)^2}}$ $^*n = 4$	$\alpha_{sf,2} = \frac{1}{3}\sqrt{\frac{1+\Delta^2}{1+(\beta+2\cdot\Delta)^2}}$ $^*n = 6$	$\alpha_{sf,3} = \frac{1}{4}\sqrt{1+\Delta^2}$ $^*n = 4$	$\alpha_{sf,4} = 1$ $^*n = 2$

5.4. Constant coefficient

The third approach, and the simplest, effort-wise, has the same concept used until now. For this approach, each base plate category will have a unique and constant coefficient, which will result from the calculation of the smallest value of the shift of forces factor. The formulations of the second approach will be also used for this one, with the same criterion for the total number of fasteners, plus an additional boundary condition for the dimension ratio factor, which will be limited to the range between 0 and 1, for the relevant categories.

Table 5.4 shows the shift of force factor for all categories, when choosing the constant coefficient methodology. The Tables 5.5, 5.6 and 5.7, show the range of shift coefficient factor for the categories 1,2 and 3, respectively. Notice that, for category 4 there is no need for this activity, since the resistance reduction factor in the second approach is already a constant.

Table 5.4 – Constant coefficients for all the categories.

Categories	1	2	3	4
Constant coefficients	$\alpha_{sf} = 0.309$ $^*n = 4$ $^{**}\, 0 \le \beta \le 1$	$\alpha_{sf} = 0.149$ $^*n = 6$ $^{**}\, 0 \le \beta \le 1$	$\alpha_{sf} = 0.25$ $^*n = 4$	$\alpha_{sf} = 1$ $^*n = 2$

Category 1

Table 5.5 – Calculation of the critical shift of forces coefficient, for category 1.

Δ \ β	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.5	0.497519	0.49029	0.478913	0.464238	0.447214	0.428746	0.409616	0.390434	0.371647	0.353553
0.1	0.5	0.492736	0.481302	0.466554	0.449444	0.430885	0.411659	0.392382	0.373501	0.355317	0.338014
0.2	0.5	0.488397	0.473432	0.45607	0.437237	0.417728	0.398167	0.379007	0.360555	0.342997	0.326431
0.3	0.5	0.484679	0.466905	0.447624	0.427652	0.407625	0.388011	0.369121	0.351146	0.334186	0.318278
0.4	0.5	0.481664	0.461774	0.44117	0.420511	0.400276	0.380789	0.362245	0.34475	0.328339	0.313006
0.5	0.5	0.479353	0.457965	0.436519	0.415514	0.395285	0.376036	0.357874	0.340839	0.324922	0.310087
0.6	0.5	0.47769	0.455321	0.433411	0.412311	0.392232	0.373288	0.355519	0.338917	0.323443	**0.30904**
0.7	0.5	0.476586	0.453653	0.431567	0.410551	0.390722	0.372123	0.354746	0.338549	0.323473	0.309448
0.8	0.5	0.47594	0.452769	0.430721	0.409918	0.390405	0.372174	0.355181	0.339365	0.324651	0.310963
0.9	0.5	0.475657	0.452494	0.43064	0.410141	0.390988	0.373136	0.35652	0.341063	0.326683	0.313299
1	0.5	0.475651	0.452679	0.431131	0.410997	0.392232	0.374766	0.358517	0.343401	0.329332	0.316228

Category 2

Table 5.6 – Calculation of the critical shift of forces coefficient, for category 2.

Δ \ β	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.333333	0.331679	0.32686	0.319275	0.309492	0.298142	0.285831	0.273077	0.26029	0.247765	0.235702
0.1	0.32849	0.320868	0.311036	0.299629	0.287257	0.274439	0.261588	0.249	0.236878	0.225343	0.214459
0.2	0.315621	0.304047	0.291492	0.278485	0.265444	0.252671	0.24037	0.228665	0.217621	0.207262	0.197583
0.3	0.298416	0.285101	0.27175	0.258674	0.24608	0.234097	0.222791	0.212186	0.202277	0.193041	0.184445
0.4	0.28034	0.266851	0.253859	0.241497	0.229833	0.218893	0.208671	0.199143	0.190275	0.182026	0.174351
0.5	0.263523	0.25069	0.238583	0.227226	0.216615	0.206725	0.197519	0.188955	0.180988	0.173573	0.166667
0.6	0.248859	0.237013	0.225945	0.215629	0.206027	0.197094	0.188784	0.18105	0.173845	0.167128	0.160858
0.7	0.236497	0.225699	0.215649	0.206299	0.197601	0.189505	0.181965	0.174934	0.16837	0.162236	0.156494
0.8	0.226243	0.216434	0.207309	0.198815	0.190904	0.183528	0.176642	0.170206	0.164183	0.158537	0.153239
0.9	0.217789	0.208866	0.200555	0.192805	0.185572	0.17881	0.172482	0.166552	0.160986	0.155755	0.150831
1	0.210819	0.202673	0.195069	0.187961	0.181309	0.175075	0.169224	0.163726	0.15855	0.153673	**0.149071**

Category 3

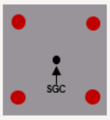
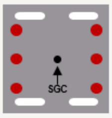
Table 5.7 – Calculation of the critical shift of forces coefficient, for category 3.

Δ	α_{sf}
0	**0.25**
0.1	0.251247
0.2	0.254951
0.3	0.261008
0.4	0.269258
0.5	0.279508
0.6	0.291548
0.7	0.305164
0.8	0.320156
0.9	0.336341
1	0.353553

5.5. SUMMARY

All the methods can be summarized in Table 5.8. Interesting is, the more generical the methodology is, the more complex it is, and more effort is required for the implementation. The solutions do not share the same result accuracy, but all of them provide more realistic and satisfactory results. The decision of the solution, for each specific case, will move according to the requirements and criteria of each scenario. A deep analysis of the pros and cons of all the solutions, likewise the effort versus the benefit, will be the subject of the next chapter.

Table 5.8 – Summary of the methodologies for shear force calculation.

Categories	**1**	**2**	**3**	**4**
Models				
Constant coefficients	$\alpha_{sf,1} = 0.309$ $* n = 4$ $** 0 \leq \beta \leq 1$	$\alpha_{sf,2} = 0.149$ $* n = 6$ $** 0 \leq \beta \leq 1$	$\alpha_{sf,3} = 0.25$ $* n = 4$	$\alpha_{sf,4} = 1$ $* n = 2$
Specific function coefficients	$\alpha_{sf,1} = \frac{1}{2}\sqrt{\frac{1+\Delta^2}{1+(\beta+\Delta)^2}}$ $* n = 4$	$\alpha_{sf,2} = \frac{1}{3}\sqrt{\frac{1+\Delta^2}{1+(\beta+2\cdot\Delta)^2}}$ $* n = 6$	$\alpha_{sf,3} = \frac{1}{4}\sqrt{1+\Delta^2}$ $* n = 4$	$\alpha_{sf,4} = 1$ $* n = 2$
General function coefficients	$\alpha_{sf} = \frac{\sqrt{\left[\frac{L}{n}\right]^2 + \left[\frac{\Delta \cdot L}{n}\right]^2}}{\frac{L_{Load}}{\gamma} \cdot \sqrt{1^2 + (\pm\beta+\Delta)^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2}}$			
General formulation	$\sum V_{Z,Load} \geq \sum V_{Y,Load} \rightarrow V_{1\ and\ 2,res} = \frac{L_{Load}}{\gamma} \cdot \sqrt{1^2 + (\pm\beta+\Delta)^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2}$ $\sum V_{Z,Load} < \sum V_{Y,Load} \rightarrow V_{1\ and\ 2,res} = \frac{L_{Load}}{\gamma} \cdot \sqrt{(\pm\beta+\Delta)^2 + 1^2} + \frac{L_{Moment}}{2} \cdot \sqrt{{\omega_y}^2 + {\omega_z}^2}$			

6
CONCLUSION AND OUTLOOK

6.1. OBJECTIVES ACHIEVED

The development of a new calculation methodology for shear force distribution in all the current structures available in Profis MSE, and also for the next to come, was the main target of this work. Clarity of the objective for this research was crucial to identify all the procedures, and their challenges, and achieve accurately the required solutions. Four possible solutions were developed in the scope of this research, and each of the stages, defined in the first chapter, was discussed and incorporated in all the chapters of this study.

The first chapter was essential for the project management of the research. The definition of weekly targets supports understanding the course of the project and clarifying the direction that the project should go. Clear milestone helps to maintain the feasibility of the work and to respect each deadline. Defining the framework of the project at the beginning is essential for the success of the work and it was well explored in this chapter.

The second chapter brings the comprehension of the investigation. The relevant subjects for the study were explained, likewise the current situation of the calculation methodology for shear force and its critical cases. In other words, the problem was exposed, as well as what is expected to be the scope of this work and a first thought of the required improvements.

The third chapter is the continuation of the research, where the physical tests were explained and the content to define the base assumptions was analysed. Later, the tools for the development of a new calculation methodology were defined. Case studies were chosen according to different parameters, and different analyses, and the calculation model for shear force in fasteners was explained, likewise how the calculation is executed in the case studies. At the end, the differences of the shear force calculation in fasteners, under different boundary conditions are detailed.

The fourth chapter shows the development of the methodology itself. From the scratch of the initial approach, each defined parameter is covered and implemented in the formulation. The steps of the methodology were detailed, and it ends with an analysis of the general formulation.

The fifth chapter exposes the final stage of the work for the company, where the challenges for a software implementation were identified and simplified different solutions were detailed, together with the calculation methodology to achieve each of them. The chapter was an essential engineering case, where the best solution might not be feasible, and alternative solutions needs to be deep investigated. Approaches easier to be implemented, but at the same time avoid decreasing quality of the developed work.

The sixth chapter, and the last of this research, starts with an overview of the objectives achieved, as well as the development made per chapter. Moreover, an assessment of the solution is made, and the chapter ends with an outlook of the future investigations of the topic.

6.2. REFLECTION OF RESULTS

In Table 6.1, a summary of all the methodologies is described, together with the advantages and disadvantages of each of them. All the solutions have their own particular relation of effort versus benefit, and it can be nicely understood in the Benefit-Effort Matrix, shown in Fig. 6.1. The matrix is defined as a chart that details the benefit that a potential solution can bring versus the effort in terms of time and resources required. For the analysis of the chart, the current methodology will be named "X" and all the solutions will be numbered according to the ease to be implemented:

1. Constant coefficients;
2. Specific function coefficients;
3. General functions coefficients;
4. Generical formulation.

Table 6.1 – Advantages and disadvantages of the methodologies for shear force calculation.

Solutions	Methodologies	Advantages	Disadvantages
Constant coefficients	$\alpha_{sf} = constant$	• Requires low effort to be implemented; • No calculation needed for the shift of forces factor;	• Super conservative for mostly of the cases; • Do not provide realistic results; • Only one factor per base plate category.
Specific function coefficients	$\alpha_{sf} = specific\ funciton\ per\ category$	• Requires medium effort to be implemented; • Provide satisfactory and realistic results;	• Base plates still need to be grouped in categories; • Four functions need to be added in the calculation routine;
General function coefficients	$\alpha_{sf} = general\ function$	• Provide high satisfactory and realistic results; • Specific coefficient for each case.	• Requires high effort to be implemented; • High number of factors need to be created;
General formulation	• Resultant shear force calculation; • Identification of critical fasteners; • Shift of forces.	• Provide high satisfactory and realistic results; • Shift of force coefficient not needed.	• High number of factors need to be created; • New methodology needs to be created, as there is no resistance reduction coefficient.

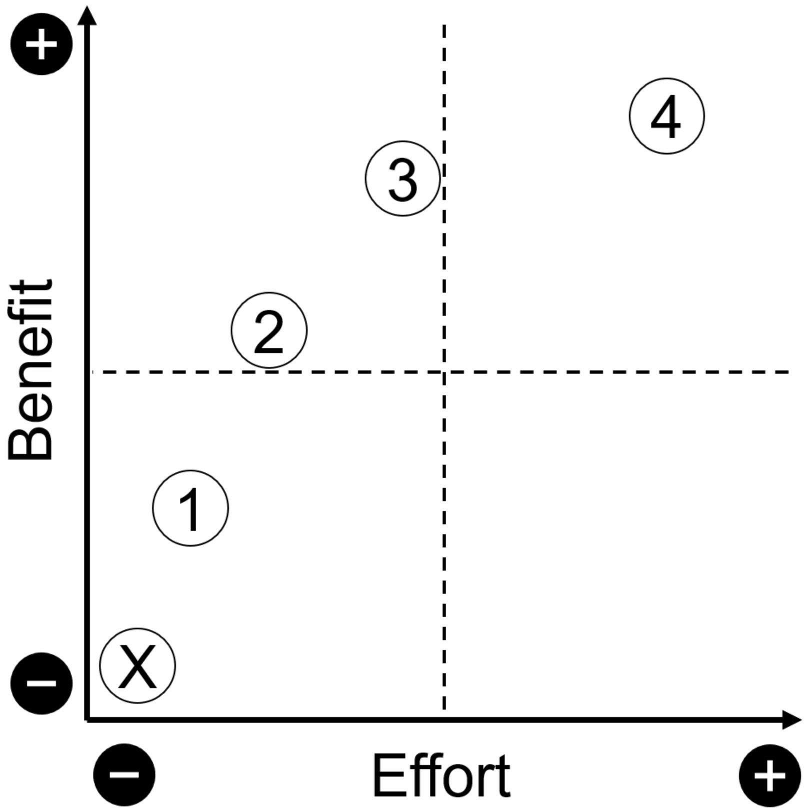


Fig. 6.1 – Benefit-Effort Matrix for all the solutions.

6.3. FURTHER INVESTIGATIONS

A next step for the constant improvement of the steel structural calculation software, especially the Profis MSE, is the implementation of a calculation methodology for the axial force, in the case of a fastener with a large washer.

Depending on the diameter of the washer, the fastened material (for our research case, the steel base plate) will be supported by the washer (and not by the base material, as per the examples mentioned during this work). This happens when the diameter of the washer is higher than the clearance hole of the fastened material (Fig. 6.2). Moreover, the transfer of axial force from the fastened material goes to the washer, which will be compressed. The material of the washer, in other words, how much the washer can be compressed, together with its height, are essential parameters to dictate how much the washer will be relevant for the calculation of the neutral line in the cross section of the joint of the structure (Fig. 6.3). Furthermore, different neutral line coordinates will be directly reflected in the amount of tension and compress forces distributed for each fastener.

Possible approaches for further investigations on this topic are:

- Reformulate the calculation of the neutral line (mentioned in chapter 2), considering the washer;
- Create a coefficient for the utilization procedure, for this case applied to the tension part of the equation. The factor should reduce or increase the resistance (or force) according to the incorporated changes made by the presence of the washer.

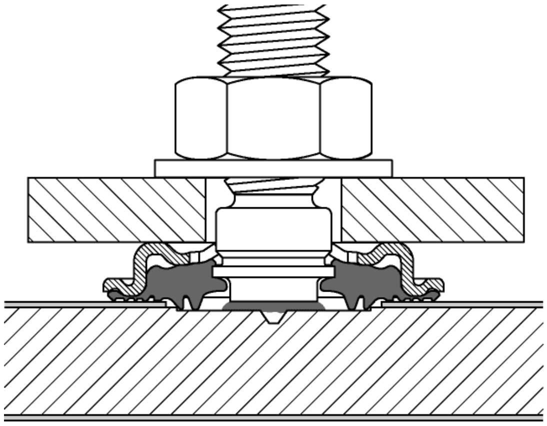


Fig. 6.2 – Fastened material compressing the washer and not the base material.

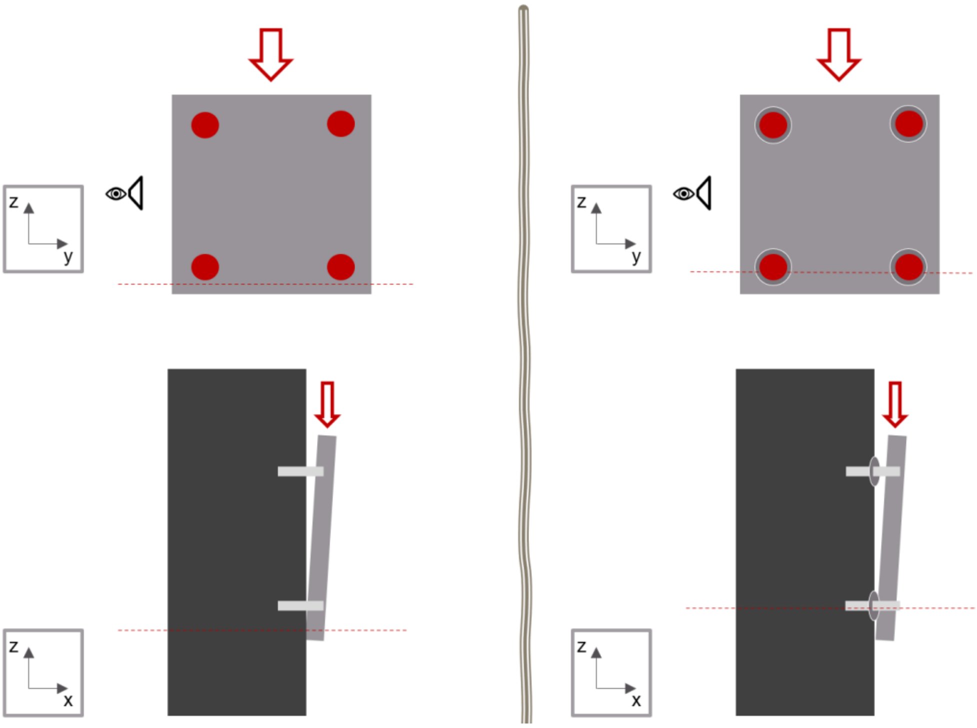


Fig. 6.3 – Estimation of the neutral line position, for the case without washer (left) and with washer (right).

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