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EXTENDED ABSTRACT

CONSTRUCTION TECHNOLOGY OF STEEL BUILDINGS
STUDY OF EURO TOWER BUILDING

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October2010

1. Background, Objectives And Methodologies

The aim of this paper is to provide a detailed characterization of the construction of a steel building in all its phases, project, fabrication and assembly. A case study is analysed consisting in the construction of EuroTower building, located in Bucareste; Romania. All the steel structure was manufactured and assembled by Martifer.

This paper analyses the quality control undertaken during the fabrication period (January –November 2008). The objective of this study was to find out which is the phase of fabrication where the largest number of non conformities were detected and the correspondent causes. Repairing costs are also quantified.

A statistic study was carried out in order to assess a quality control of on site welding.

2. Euro Tower Building

Cascades Park Plaza Office Building (CPPOB), now designated as Euro Tower Building, has an architectural capacity of 1630 persons, being daily occupied by 1430 persons. It is owned by the Cascade Group, a Dutch company engaged in the real estate business, mainly in Eastern Europe.

The budget for its construction was about 25 million Euros. Initially, the construction was expected to take place between June 2007 and February 2008 (21 months).

The ground area of the building is 1.821 m^2 and its height is 94 meters.

The total area is 26.600 m^2 (9100 m^2 of parking below the ground level and 17.500 m^2 of office areas)

The architecture development was made by Dorin Stefan Birou Architectura office and Chapman Taylor office. The stability project was developed by Popp & Associatii with the advising of WSP Group.

The main contractor was Bovis Lend & lease. However, Martifer was subcontracted to manufacture and assemble the steel structure. The initial project had defined S460 steel, which was impossible for Martifer to stock on time. To solve this problem, Martifer redefined the project, changing the class of steel to S355. The new project was put together by Tal Projecto. Another change was skipping the bracings dampers.

2.1. Original Project

The initial project comprises tubular bracing in all modules of northwest and east facades and front corner of the body of 19 floors. At first the bracing profiles were concentric type H, and the interior modules (two in front and three in North east front) had shock absorbers. The facade of the corner bracing is arranged in "inverted V" **[1]**.

The elevators' core, existing in the remaining facade (south) had bracings in its full extent, even in small frames, requiring the presence of nearly vertical bracings.

The inclinated facade had bracings whose alignment corresponds to the bracings placed in the main facades. The body of 5 floors, didn´t have bracings. Instead lateral actions were mitigated by "Full Moment Resisting Frames".

The main sections used were, in columns, 400x900 HD profiles, and in beams, HEA 500 and HEA 650. In bracings of the exterior modules were used HEB and HEM profiles. In the inner modules the bracings have circular hollow sections with 273mm on diameter by 16mm radius. The steel class was S460 and the total weight of the structure was 3000 tons **[1]**.

The floors were made of fungiform slabs in reinforced concrete (C25/30), with a thickness of 35 cm, so that the construction process would be alternated between the steel module assembling and concreting of the corresponding slab.

The structural connections of buildings would be provided by:

- Site welding between beams and columns;
- The butt connections were ensured by butt welding and bolting, (varying according to the area of the structure) with copper.plates in webs and flanges of the profiles;
- Bolting conections between bracing elements and beam-column system;
- Articulated connections formed by spherical pins formed in sections that support dampers.

2.2. Final Project

2.1.1. Analysis Of The Original Project

The damping system of the building was composed by 180 fluid viscous dampers (10 on each floor) of 225 Mton each. As mentioned, these would be applied in concentric bracing modules existing in inner east and west facades and in the extreme modules of south facade, including the elevators core since 6th floor until top.

This system was characterized by its high cost due to the number of dampers used and did not constitute the ideal structural solution in relation to the weight of the structure. Moreover, this solution becomes redundant because the dampers are not in the main resistant element to horizontal actions of earthquakes, because bracings were already assuming this role.

2.1.2. Legal And Regulation Requirements

The main legal requirement for the new structural solution is the obligation, established by Romanian standards, to name a checker designer that verifies if all the procedures and regulations are fulfilled. Another main constraint consists in respecting European (Eurocode 8) and Romanian seismic standards, P100-1 (2006). As expected, there are discrepancies between these two standards. This happens because one is only based on the Romanian reality, restricting its applicability to this country, while EC was prepared in a generalist perspective, applicable to the entire European territory. Thus the confluence of the two regulations in the design of the building was not always peaceful. An example of these differences is the blurring of land types according to the Romanian regulation, which provides different zones of Romania with response spectra based on a single soil type.

2.1.3. Structural alternatives analysed

Surveys carried out in the original project, outlined in Figure 1 concluded that the structure had a very high frequency vibration, which led to significant stresses. Therefore, the most logical alternative would be to create a more flexible structure **[1]**.

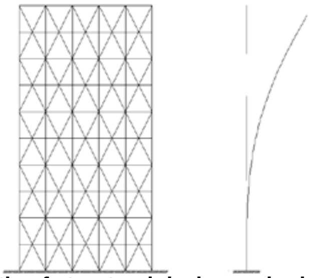

Figure 1: Schematic of structural design and original mode of buckling (adapted from [1])

On the other hand, it is known that deformation between floors in a seismic event often reaches its maximum value rules (according to the P100-1 (2006) and EC8) in structures with high flexibility. This is still magnified by the fact that the building, by architectural imposition, does not have a core or bearing walls of reinforced concrete. Thus, deformations control is assured by the bracing system. Therefore, the major changes were made to these structural elements. A bracing system was initially predicted in the end modules of longer facades (North West and East) and in the lifts core frames placed in parallel to the south facade, as depicted in Figure 2. Thus, the dampers would be removed (existing in tubular bracings of the inner modules). With these modifications the structure would have a well-defined behaviour concerning its resistance to horizontal actions. Moreover, this solution allowed the reduction of stiffness on the lifts core, which due to its peripheral position contributes significantly to the torsion stress of the building, which justified the adoption of dampers in the original project. So the modal analysis performed indicated a decrease in participation of the main modes of torsional vibration, consisting essentially on translations in directions perpendicular to each other **[1]**.

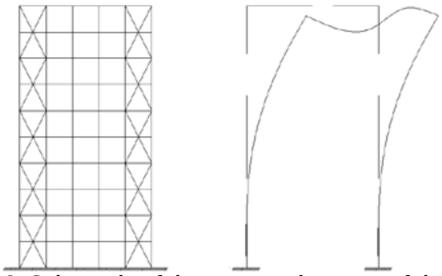

Figure 2: Schematic of the structural system of the first alternative and buckling mode (adapted from [1])

The behaviour in response to horizontal actions was no longer a "wall" type behaviour, which deformed doesn´t have curvature inversion. The behaviour started t to resemble the deformed of two "walls" connected by non-rigid connection. Thus significantly reduces the stiffness of the building, which is expressed in increasing its fundamental period. This system also allows a greater mass participation in the first vibration modes, which permit to predict accurately the consequences of structural vibration. (Lower frequency modes).

Thus, this structural system has good performances in terms of security of the collapse, because it allows the reduction of seismic stress imposed to the building. However, the modal analysis indicated the existence of excessive deformations on the floors, which are incremental, developed with building height. Due to this there were deformations recorded over two meters on the higher floors. This problem was easily solved by incorporating resistance elements, such as cores or concrete walls, "Full Moment Resisting Frames", characterized by rigidly response to bending. However, the solution would have to pass by the bracing system due to architectural impossibility of including these resistant elements **[1]**.

The main goal was to reduce the deformation of the floors while maintaining the flexibility of the structure, essential to ensure the safety to collapse. To accomplish this objective the “wall” type behaviour had to change to“frame-wall” type behaviour. This was achieved through the inclusion of bracing in the last three modules on top of each facade. As it is evident in Figure 3, this type of behaviour enables a more controlled increase of deformations on the floors along the vertical development, because, unlike the previous system where deformed recess had the same height, the behaviour "frame-wall” has an inversion of its concavity due to the embeddedness degree conferred by the rigid connection between the beam and column of the frame.

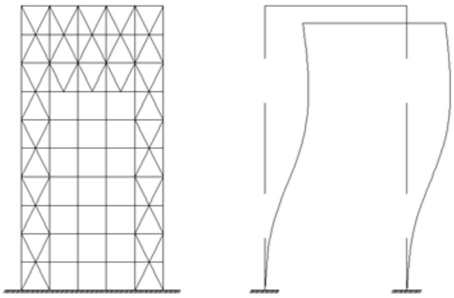

Figure 3: Schematic of the structural system of the final solution and buckling mode (adapted from [1])

The bracing system used in both end modules and last three modules on top are concentric, characterized by an effective energy dissipation, decreasing the actions on beams, so that its dimensions could be reduced, allowing the decrease of global building rigidness. With this it is possible to reduce costs and avoid possible geometric constraints. This bracing system is “V" and "inverted V" type, alternating on each floor. This system was included at the largest facades of the building (North and East). Like the previous system the structural core of elevators has three modules braced.

From the standpoint of structural behaviour, it was necessary to separate the two bodies of the building in order to accentuate the features of behaviour cited above. It is readily apparent that a structure with a more irregular shape, in this case with a sharp retreat on its height development, will have less vibration modes expected, with lower mass participation in the main modes, where the torsional component could become significant. It can also generate additional efforts in the retreat area, which would force to use much larger structural elements **[1]**.

The floor structure consists on a mixed solution, where the girders are connected to the peripheral structure by hinges, which makes that this elements don´t have horizontal solicitations.

A mixed solution would make the structure lighter, which substantially reduces the seismic forces and displacements, allowing for even greater structural and cost optimization.

Unlike the original project, it was stipulated that the connection would be assured by bolting, due to practical reasons.

It is known the better behaviour of bolted connections to cyclic loading and unloading, concerning to welding. Apart from complying the regulations of EC8 there are other standards of the correct behaviour of connections **[1]**:

- Failure should not occur in the web of column and in the beam-column intersection, avoiding column failure on a floor;
- Ductile failure (crushing) should prevail instead fragile failure (Cut)

- Decreasing the drilled area of plates section, ensuring that fracture will occur in full sections, prevailing ductile fracture above fragile fracture;
- Use types of connection has already been tested experimentally;

2.1.4. Materials

Concerning the main structure was used steel S355 J2 plates with a thickness of 50 mm and S355 JO for plates with thickness less than 50 mm. In the floor structure was used S275 JO steel, C25/30 concrete and reinforced steel PC52.

2.1.5. Foundations

The solution sought to deal with bad terrain features found in this part of Romania. Therefore, not only the seismic conditioning already mentioned, but also the bad characteristics of soils, led to adopting an indirect foundations solution. The whole system is described:

- "Munich" retaining wall, with the same depth of piles. Its behaviour is similar to a continuous pile allowing the dissipation of the significant seismic stresses imposed on facades. It also has the structural function of resisting the impulses of the soil during construction and during the lifetime of the building;
- Group of piles. This piles are extensions of the columns (Figure 4), whose function is to transmit the vertical ground actions;

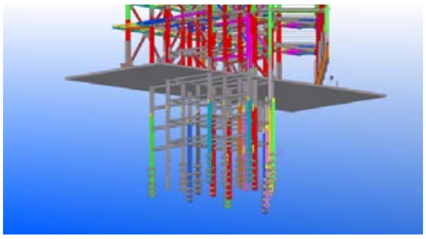

Figure 4: 3D model of the Euro Tower foundations

- Bottom Slab for heading the piles. It has also functions of mat foundation (Figure 4). Furthermore it resists to stresses caused by differential displacements between piles and retaining wall.

The construction process was "Top-Down" in an attempt to use all the available space on site **[1]**.

3. Structural components fabrication

3.1 Cutting

Cutting is a production stage where detailed planning assumes a significant importance in order to obtain the best use of the initial element, be it a profile or a plate. In this field, CNC softwares *(Computer Numerical Controlled)*, become an unquestioned asset, enabling the execution of a detailed cutting plan, where all necessary information is downloaded into the computer cutting machine.

Cutting can be performed by various methods depending on the type of steel section of the piece and its dimensions.

3.1.1. Plates

Cutting is almost exclusively performed by thermal processes, namely the oxy-fuel cutting and plasma jact cutting. Both technologies are based on energy principles, in which the steel reaches its melting point allowing the separation of the material.

- Oxi-fuel cutting;

The main consumable of this technology is acetylene, which engages the exothermic reaction between oxygen and steel.

The equipment consists of a cutting table where the plate is positioned. A track system is bounded to this table, where a sliding cross bar is installed supporting the cutting device, consisting of multiple nozzles or cutting torches (Figure 5).

Figure 5: Equipment for oxy-fuel cutting [ph: personal archive]

This technique has the ability to cut any kind of structural steel up to thicknesses of 120mm and is commonly used in preparation of plates that form the composite profiles section. The cut surface is irregular, characterized by the existence of burrs, being necessary its treatment, which usually consists of burr in the cutting edges. The heat affected zone is significant, which may affect the quality of welds in these areas.
The cutting precision is high, with a slit narrow, which reduces the steel waste due to cutting. This technique allows good cutting speeds, depending on the thickness of the plate **[2]**.
Due to its high accuracy, it allows complex cutting geometries with angular and curvilinear shapes.
It should be noted that the equipment used for this technique should be inspected periodically in accordance with section 12.3.2.1 of EN 1090-2:2005.

- Plasma jact cutting;

The consumable gas is usually nitrogen. However is also possible to use hydrogen and argon **[2]**.
There are two techniques of plasma ejection: the injection of compressed air or water injection. The production of metallic structures only use the plasma cutting with water injection, because it enables the cutting surfaces with better finish, so that only this will be featured in this text. (Figure 6) **[3].**

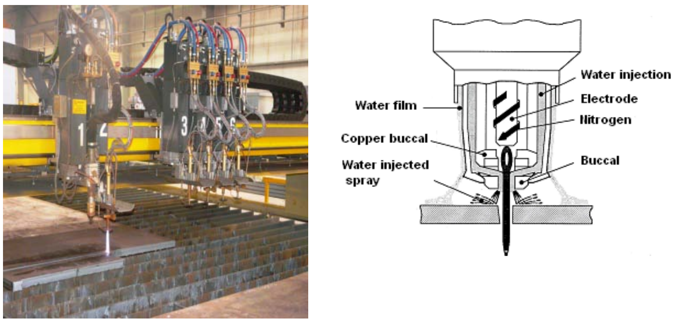

Figure 6: Details of implementation of plasma arc cutting and representative scheme of a plasma cutting torch with water injection [ph: personal archive] [3]

This technology is used for preparation of plates, allowing cutting all types of structural steel, limited to elements with thicknesses less than 30mm. However, for current intensities of 1000 Amperes maximum thickness can reach 125mm in stainless steel **[3]**. This method has a high precision cutting with smooth surfaces. The cutting speed is very high, which is a very significant advantage not only regarding the efficiency of the process. This fact also permit less changes in the steel characteristics, since the zone thermally affected by the cut is very small, consisting on only a few millimetres in plates up to 50mm thick. Waste is practically ignored, since the thickness of the slit cut is reduced. On the other hand, the losses of the characteristics of steel alloy by vaporisation due to exposure and contamination of the atmosphere of the arc at high temperature corresponds to a depth of approximately 0.1 mm **[4]**. The Oxi-cut allows the execution of sections of curvilinear and angular shapes. The cost of this technology is relatively low because additional supplies such as nitrogen have commercial purity in opposite of conventional gas mixtures.

- Guillotine;

It is a mechanical process to cut sheet plates, as top plates or cleaver plates. The maximum thicknesses applicable to this method are 14mm for steels whose yield strength is less or equal than 355 MPa and 10mm for steel which yeld strength is greater than 355 MPa. The guillotine, usually hydraulic, submits the element to a cut stress, laminating steel until it breaks. It induces some imperfections in cut surface, like roughness and can smash the plate, in the surrounding area of the cut surface **[2]**. The surface treatment by cutting burr should not exceed 0.5 mm in depth **[6]**.

3.1.2. Profiles

Usually the cut of these elements is performed by longitudinal band saw, rotary tape or circular disc saw, because it has good production rates on cutting this type of structural components. Sawing only is able to cut simple geometries, like straight, perpendicular or oblique cuts, with a maximum angle of 45º. The circular disc saw often has 5mm thick. The maximum dimensions of the piece to be cut are determined by the disc diameter. Taking into account this parameter is still possible to group profiles, cutting each group simultaneously so that can increase productivity. Usually the cut is always executed with the flanges on vertical position **[4]**. The longitudinal band saws and tape rotation are less able to cut concerning the work piece dimensions. The cutting accuracy is identical to the saw disk **[4]**. The cut surface shows some roughness, implying their treatment by burr.

3.2. Drilling

Drilling is controlled by geometric and numerical control programs (CNC) that define precisely the arrangement of holes, as well as its diameter. The methods of drilling include **[5]**:

- Punching;

  Used on thin plates, such as top plates or cleaver plates, performed by percussion of a cylindrical piece against the piece. Its application is limited to metallic elements of class 1 and 2[1]. Moreover EN 1090-2, Point 6.6.3 also explain some restrictions to the use of drilling techniques, taking into account the type and thickness of the steel piece. Punching holes are allowed for steels with $f_y \leq 355MPa$ and for thicknesses that not exceed 25mm, where nominal thickness of the piece is not greater than the nominal hole diameter. For steels with greater yield strength, this technique is restricted to 14 mm of maximum thickness **[6]**. Punching can also cause distortion of steel in the area surrounding the hole, which is limited according to EN 1090-2, Section 6.6.3. The diameter of the hole by punching should be about 3mm less than the desired diameter, since the rest is done by chuck. The holes are necessarily boring, regardless of drilling techniques for classes 3 and 4, being exempted from this process, classes 1 and 2.

- Drilling;

  Usually used in drilling metal profiles, where holes are made by cutting chipping, caused by the rotational movement of the drill. The process is aided by an emulsion that softens the contact surface between the drill and the work piece, to facilitate drilling;

- Plasma;
- Oxy acethilene arc;

Laser, Plasma and oxy-fuel cut techniques are based on the same working principle of cutting, being already described in the previous section.

3.3. Welding

Welding is a procedure that allows the continuity bound between metallic elements forming a structure. It consists in the merge of material, by increasing temperature and the connection is provided by the addition of a filler material that melts with the steel. **[4]**
Compared to bolted connections welding has two main advantages, namely to reduce substantially the weight of the structure, since it requires no connection plates, and provides more effective connections concerning fire protection and corrosion. **[4]**
The European standards involved in welding process are shown in Figure 7 .

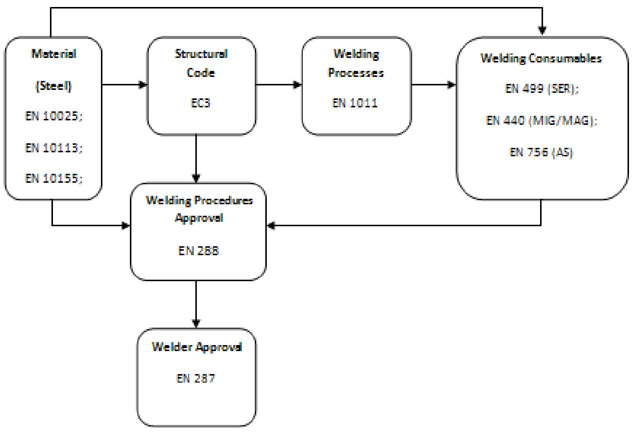

Figure 7: Representation of the relationship between standards related to welding. Arrows indicate conditioning. (Adapted from [4])

3.3.1. Welding process

- Electrode welding

  This is one of the most used welding processes due to its simple technology and easiness to perform in the workshop and on site. In this case, it is necessary to provide protection to the weather constraints. **[4]** Their versatility allows its use in various jobs, from welding repairs, fillers up of strands in areas of difficult access, such as sharp corners or interior areas of pieces. The process involves the connection of these metals by melting and of the consumable (electrode coated), due to the heat, produced by an electric arc established between the electrode and the work piece. This weld bath

[1] Execution classes consist on categorize metal structures depending on the level of quality required. The requirements for each class of execution are given in Annex A3 of EN 1090-2.

composed by metal and fusion material of the electrode is deposited along the joint, ensuring the welding between the parts **[7]**. The electric current used in welding can be direct or alternating voltage varying between 16 and 40V. Intensity also varies between 30 and 500A. However these values are dependent by the magnitudes of the coating used **[7]**. This process is outlined in Figure 8.

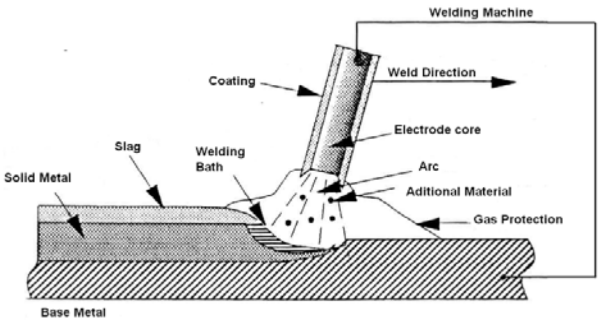

Figure 8: Principle of operation of the electrode welding [7]

An electrode consists on a rod (core metal) coated with a layer of mineral or organic material (coating). This coating has an electrical resistance function, allowing the formation of a stable arc and preventing the formation of parasitic arcs laterally to the rod, where the gasket welding has some depth. Moreover, the coating melt (slag), by incorporating the weld bath, improve their physical behaviour in terms of density, viscosity and surface tension, allowing the realization of various positions of welds, including overhead welds, where the material is deposited against the action of gravity. Its presence in the molten bath contributes to the protection against outside contamination of atmospheric gases **[7]**. The position of the electrode in the work piece is very important, because the angle can compromise the correct deposition of the slag, losing the its protective effect. In other hand slag inclusions in the weld can significantly reduces the mechanical strength of the weld **[7]**. This process allows to weld all types of steel used in steel construction, micro alloyed steel and high corrosion resistant steels.
Its use is limited to thicknesses greater than 1.5 mm, because for lower thicknesses the work piece melts before obtaining a stable weld bath. However it is impractical to run this welding process with a thickness of less than 5mm string, because the thickness of the electrode does not permit. There is no upper limit of thickness of parts to be welded, however there other processes more suitable in this cases **[7]**.

- MIG/MAG welding;

It has wide application in weld metal construction because it welds all kind of metals, with emphasis on structural steels and high strength, stainless steel and aluminum **[7]**.
Welding is performed by an electric arc formed between a consumable electrode wire, supplied continuously through a coil and the work piece. This arc will allow the fusion of electrode wire and work piece, forming the weld bath, which is deposited on the joint, completing the weld (Figure 9). This process is protected from outside contamination by gas supplied to the welding environment. It was initially used an inert gas such as argon or helium or mixtures, corresponding to the MIG welding (Metal Inert Gas). However, the use of an active gas (carbon dioxide or mixtures) leads to improved efficiency, making it more economical. This variant is called MAG welding (Metal Active Gas) **[7]**.

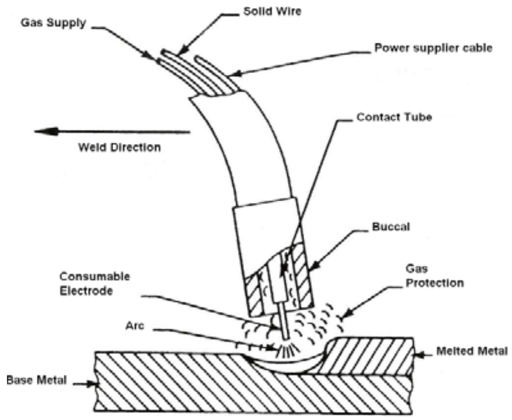

Figure 9: Operating principle of MIG / MAG welding [7]

A variant of MIG/MAG welding is the cored wire welding (CWW). This process is particularly important because it can dispense gas protection of outside contamination, so that is ideal for outdoor welding where the wind does not allow the gas supply protection **[4]**.

- Submerged arc welding;

This welding process results from the simultaneous fusion of the edges of pieces together. The fusion is caused by the heat supply system due to an electric arc established and the Joule system. The molten bath is completely covered by a granular material which suffers a partial melting, forming the slag (Figure 10). The function of the material is similar to the coated electrodes. Thus, the entire process is shielded from the outside, using safely high currents (200 to 2000A), since it reduces the occurrence of metal splash. This allows higher yields and greater capacity for penetration welding **[5]**.

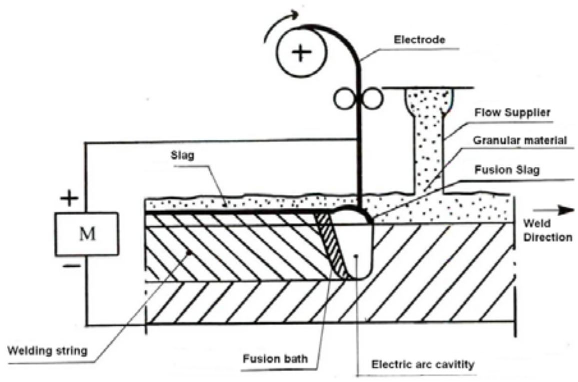

Figure 10: Working principle of Submerged Arc Welding [7]

3.3.2. Execution

- Welding position;

The welding position is directly related to the difficulty of execution and thus to obtain a weld that meets the defined quality parameters. Therefore, the training and qualification of welders to perform certain welding positions is crucial to ensure quality.
Three positions of welding can be identified, listed in order of increasing its difficulty: low welding, vertical welding and overhead welding, being represented in Figure 11.

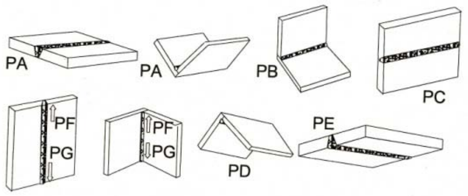

Figure 11: Welding positions: (PA) (PB) low welding; (PC) horizontal welding of vertical pieces; (PF) vertical upper welding; (PG) vertical downer welding (PD) overhead welding [4]

- Type of joints;

The most common connections in welded structures (Figure 12) are butt welds, T-butt welds, fillet welds and lap welds.

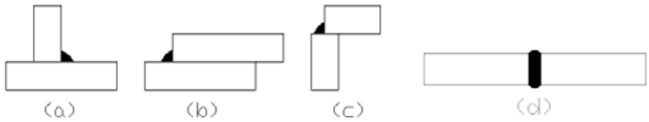

Figure 12: Types of weld joints; (a) T-joint; (b) Lap joint; (c) corner joint; (d) Butt joint (adapted of [4])

- Types of welding;

Depending on the type of joints, it is possible to distinguish various types of welds. The most distinctive ones, because its large application in construction are butt welds and fillet welds used in T-joints, lap joints and corner joints **[4]**.

3.3.3. Quality Control Methods

- Visual inspection (NP EN ISO 5817);

Visual inspection is the non destructive inspection method more expeditious and simple, allowing the detection of defects on the surface, using simple optical devices, such as poor finish, small cracks and weld corrosion **[7]**. This method is defined in the standard NP EN ISO 5817.

- Penetrant liquid inspection (EN 571);

The test consists in vaporizing a liquid (Figure 13), allowing the identification of superficial cracks due to the different surface deposition of the liquid. So that can highlight these defects (Figure 14).

Figure 13: Liquid penetrant inspection [8]

Figure 14: identification of cracks and craters in the weld [8]

- Magnetic particle inspection (EN 1290);

The test procedure consists on inducing a magnetic field to the welding area (Figure 15). The discontinuities are detected from slight variations in magnetic field, identified by ferromagnetic particles that travel through the weld. Thus, the arrangements of particles, which accumulate along the discontinuities, will map it, and indicating its forms and extent.

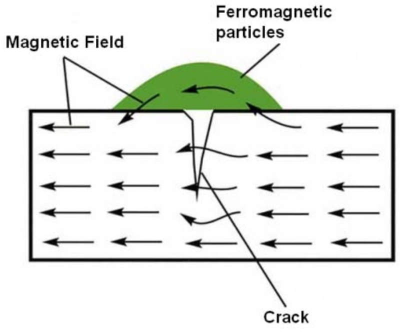

Figure 15: Magnetic particle test

- Inspection by X-ray or Isotope radiography (EN 1435);

This method is based on the same principle that common X-ray, which consists in emitting radiation (X-rays or gamma rays). Its absorption depends on the thickness and density of the welding test. The radiation not absorbed by the material due to the existence of discontinuities (changes in density), is recorded on a film, and thus easily identifiable. It has great application in detection of void volumes.

- Ultrasound inspection (EN);

The ultrasonic inspection has wide application in metalic construction, because it is a method with a high accuracy, enough to ensure an efficient control of welds in steel structures. This method allows the measurement of defect thicknesses, detection of volumetric interiors such as voids, cracks and discontinuities of material. It is based on measuring the propagation time and amplitude of the ultrasound. The equipment consists of transducers sending / receiving and a recording device (Figure 16)

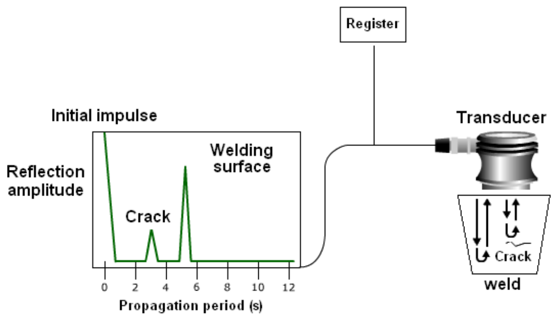

Figure 16: Working principle of ultrasound welding inspection

- Eddy current inspection (EN);

It consists in detection of variations of electric condutivity due to material variations.

3.4. Surface Treatment, fire and anti-corrosion protection

Common finishing systems are usually composed by, in order of execution, mechanical shotblasting, anti-corrosion protection, and fire protection by intumescent paint **[9]**. These paints are solvent-based inks, based inks or water-based epoxy resins. (Figure 17)
In specifics, the Euro Tower building's corrosion protection was ensured by a paint coating based on a primary epoxy with high zinc content.

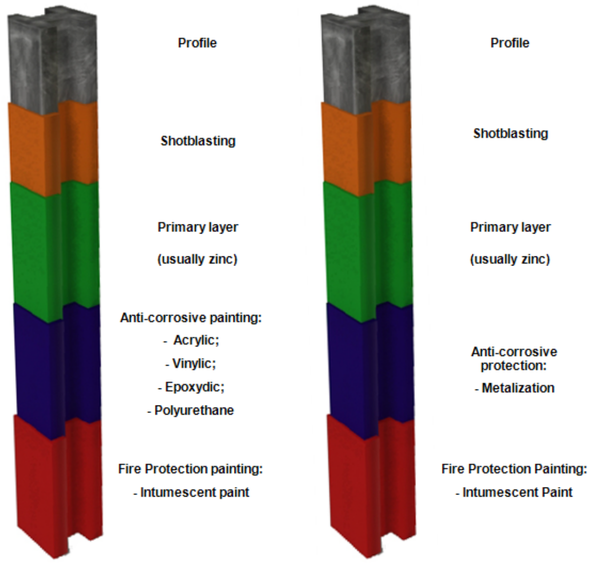

Figure 17: Usual finishing schemes in steel structures

3.5. Fabrication Quality Control

The goal of this analysis is determine the causes that lead to the anomalies detected, concerning two main variables: manufacturing phases and the departments responsible for those mistakes, since design and preparation office, until the workshop.

Costs related to these anomalies, concerning the variables already mentioned, are also quantified.

Welding consists in the fabrication phase where were detected more non conformities reports (Figure 18) (Table 1)

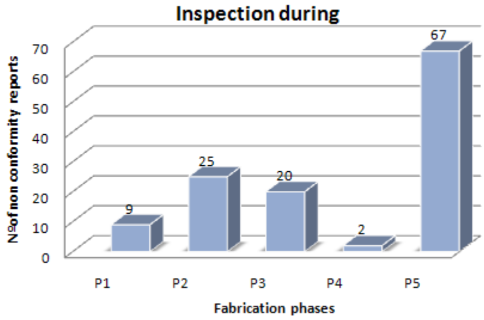

Figure 18: Number of Non Conformity Reports elaborated in each manufacturing phase

Table 1: Manufacturing phases surveyed by quality control

Subtitle:
P1 - During assembly;
P2 - After welding, before shotblasting;
P3 - After welding, after shotblasting;
P4 - Painting área
P5 - Documentation error

An anomalies distribution regarding the respective causes and reparation costs is presented (Figure 19) (Figure 20)

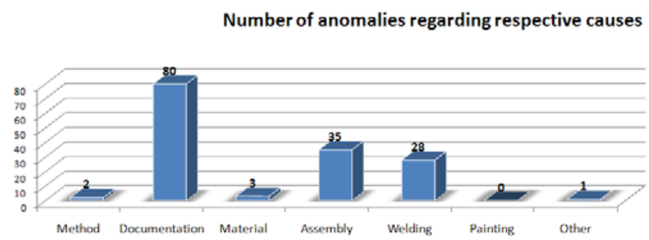

Figure 19: Number of anomalies, during the analysis period, regarding respective causes

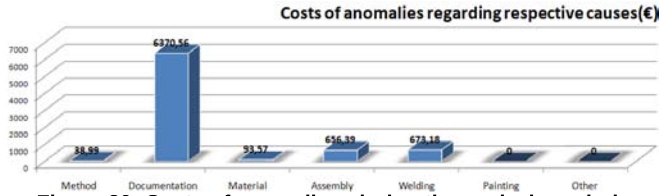

Figure 20: Costs of anomalies, during the analysis period, regarding respective causes

Documentation is one of the principals causes of the anomalies detected. Furthermore, the associated costs are much higher comparing to the rest of the causes.

This fact is directly related with the significant number of anomalies which causes refer to work piece assembly. Thus, a non mistaken documentation, concerning to manufacturing drawings and assembly plans, determines the components assembly.

On the other hand, the anomalies related to welding, consequence of documentation and execution errors have to be taken into account, given their significance in the repairing budget for this structure.

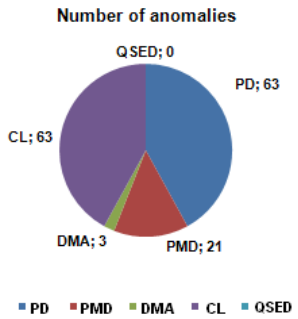

Figure 21: Anomalies distribution provoked by the different departments involved (QSED: Quality Safety and Environment Dpt. CL: Client; DMA: Material Dpt.; PMD: Project Management Dpt.; PD: Production Dpt.)

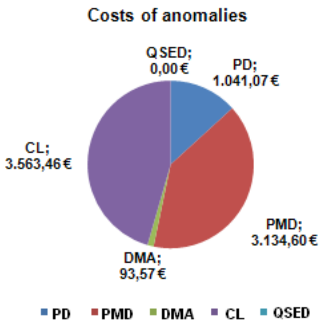

Figure 22: Costs associated to anomalies provoked by each department (QSED: Quality Safety and Environment Dpt. CL: Client; DMA: Material Dpt.; PMD: Project Management Dpt.; Production Dpt.)

The majority of the anomalies occur in the Production department (Figure 21). Crossing this information with the previous chart, which shows that documentation errors are the main cause of the anomalies detected, it can be concluded that the errors occurred aren´t related to the workshop, being associated to preparation drawings and execution support plans.

However, the chart referring to costs (Figure 22) indicates that, in spite of the production department being responsible for most of the registered anomalies, the higher cost volume is associated do Project Management Department. This fact can be explained by the complexity and detail associated to a steel structures project, specifically in joints. Thus, the costs due to project changes increase significantly.

Figure 23 and Figure 24 present the distribution of anomalies, according to number and cost, for each department where the anomalies were detected. It shows that QSED is not responsible for a higher number of reports, a fact that wasn´t supposed to happen, since the core activity of this department is to guarantee the quality of the process. Furthermore PMD replace QSED as the Department with more non conformities reported.

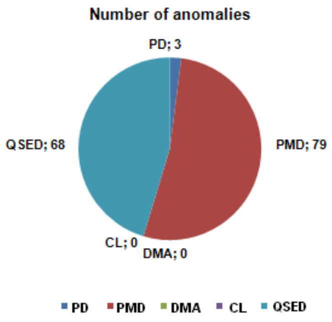

Figure 23: Distribution of anomalies reported by the different departments involved

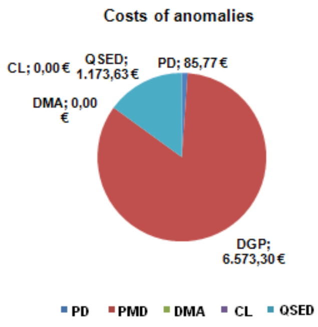

Figure 24: Costs associated to the anomalies reported by each department

4. Steel Structure Assembly

4.1. *Building Information Modelling* (BIM)

BIM consists in the establishment of dependence relationships between all the construction phases of a steel structure (project, production and assembling on site), using one single interactive work platform, that allows one to simulate virtually the three phases, not only in technical field, but also regarding costs and schedule. In this perspective it allows one to detect and solve problems that would only be notice on site **[10]**.

4.2. Construction Phases

4.2.1. Assembly Plan

It is an essential and necessary condition that the construction is based in a detailed assembly plan elaborated by the contractor. Its guidelines are defined in European Standard EN 1090-2, 9.3.

Moreover, the assembly sequence determines the material delivery schedule, important factor in urban sites, due to reduced availability of space. Thus, material deliveries should not exceed 20 tons, divided in ships of 5 tons, so that the crane can manoeuvre it easily **[4]**.

4.2.2. Structure Ground Location

One of the common mistakes in metallic construction is the difference between real position of the connection points between foundations and steel structure and project position. This fact is due to the lack of precision associated to the construction processes of concrete elements. Moreover, the lack of coordination between the steel contractor and concrete contractor can increase the possibility of mistakes. In an attempt to minimize these errors, a 3D reference system is created. The deviation is detected from the centre of gravity of the piece **[4]**.

4.2.3. Execution of Foudations and Connection to the Superstructure

In steel structures, the type of foundations depends essentially of the terrain type, number of underground floors and the height of the structure. However, for high-rise buildings, with few underground floors, comparing to the higher structure, as Euro Tower Building, piles are a foundation system commonly used

In direct foundations the connection to the steel structure is ensured by anchored bolts in concrete.

Execution and position tolerances of foundations are described in EN 1090.

4.2.4. Steel Structure Assembly

In buildings, an assembly phase (Figure 25) should consist of assembling rigid frames, so that each phase can resist to lateral actions **[11]**. Thus, the first stage is to assembly all the vertical elements (columns). In this phase it is not necessary to ensure the correct position of the elements **[5]**. The next stage is to assemble the horizontal elements (beams) and braces. The connection between these elements is ensured by one third of the total numbers of bolts. [**12]**

The assembling of these frames should be done carefully, not only due to safety concerns, but also because any damage in the coatings can jeopardize fire and corrosion protection **[4]**. Assembling tolerances are described EN 1090 Standard.

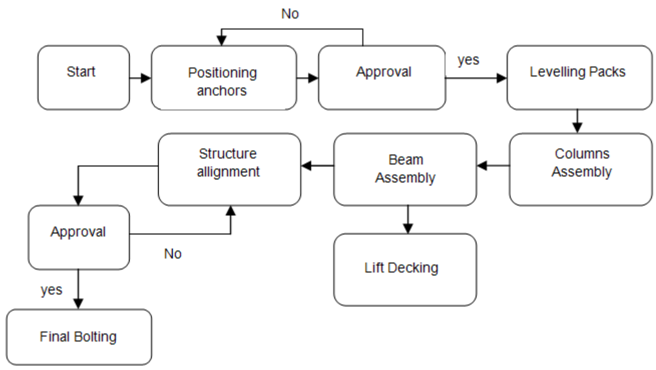

Figure 25: Assembly Sequence of a steel building (adapted from [4])

The stability of the unfinished structure, in each phase, is a concerning factor in the project of the building and in planning the assembly sequence. The stability of the structure is more critical in this stage than in the final phase, with the structure completed.

Wind and temperature assume a huge importance, because these variables consist in the most important factors of instability of partially assembled structure.

Regarding high-rise steel buildings, wind action can difficult works in high, namely, the positioning of elements and the manoeuvring of cranes. Furthermore, wind can reduce the work conditions of workers, so that the work platforms should be protected from lateral wind. To mitigate these actions, it is sometimes necessary to build temporary braces. It is very important to notice all the corrosion signs of these elements.

In this case study, the building resists to horizontal actions with permanent braces of the structure.

The steel structure was assembled simultaneously with the construction of underground floors. This fact imposed limitations to the evolution in high of the building, because basement slabs significantly reduce the buckling of columns.

On the other hand, the foundation system and underground floors were built in a “Top-Down” system. These facts required the construction of piles cap slab in the end, after the beginning of the steel structure assembly. This slab represents a significant part of foundation resistance. In spite of the small angle of internal friction, due to bad soil characteristics, the large slab area contributes a lot for the resistant capacity of foundations.

Slab concreting occurred simultaneously with structure assembly, with a gap of two to three floors for stability reasons.

4.3. Equipments

Heavy equipments used in the construction of a building are, essentially elevation devices, like fixed or mobile cranes, elevation platforms and telescopic forklift

4.3.1. Planning

All the elevation devices should be contemplated in the construction plan, as well as their positioning, load capacities and load areas. This information affects the assembly plan that seeks operational optimization of the used equipments. The main decision factors are **[4]**:

- Site Location;
- Construction period;
- Work piece weight;
- Geometric forms and dimensions of work pieces;
- Geotechnical conditions of soil;
- Material reception planning and location of storage areas;
- Assembling conditions of elevation equipments.

4.3.2. Operation

Steel pieces handling should be ideally executed ensuring the horizontality of the element in suspension. To accomplish this it´s necessary to know exactly where the gravity centre of the piece is, which can be difficult to determine due to the complex geometry of some elements. This complexity usually makes operators lack the knowledge to support their work and experience. Firstly, manoeuvres should be executed slowly and carefully to test the piece's stability in suspension, verifying it response to wind and the position. Manoeuvres should be aided by a guide-cable, tight to one side of the piece.

4.4. Assembling Details

4.4.1. Execution Details of Bolted Joints

There are several practical recommendations that should be considered in the design of bolted connections **[4]**:

- Bolting design should be executed, minimizing the variability of dimension and resistant characteristics. It should prevail the use of the same bolt in each connection, avoiding design errors in a previous stage and assembly errors;
- Approximately 90% of common bolted connections can be ensured by M20 Bolts;
- The type of joints should be standardized, with the goal of decreasing errors and increasing execution productivity;
- Connections elements (Bolts, nuts) should be supplied with anti-corrosive protection, avoiding protection on site, which execution is more difficult with worst finishing;
- Connection elements should be rationalized and well storage, due to its reduce dimensions that can be easily lost on site;
- Following the last statement, the supply bolts should be a "just in time" process, reducing significantly material lost and material oxidations.

a. Non Pre-Tightening Bolt Joints

Bolt tightening should be executed with torque wrenches. However, the first tight is executed by the effort of a man equipped with a common wrench. Tightening sequence starts by the inner bolts of a connection to the outside bolts.

Then, final tightening is given with a torque wrench **[4]**. This torque should not be excessive, in order not to damage the bolt head and its screw. On the other hand, the tight should not punch the connection plate. The difference between the elements thickness to connect should not exceed 2mm.

b. Pre-Tightening Bolt Joints

Pre-tightening prevents the connection from slipping. The initial phase is executed with a common wrench. However the permitted gap in this case between elements thicknesses is 1mm **[11]**.

The minimal values of pre-tightening in KN regarding bolts type are defined in EN 1090-2 (Table 2). Pre-tightening strength also can be determined by the equation **[11]**:

$$F_p = 0{,}7\, f_{ub} A_s$$

Where,

F_p : Pre-tightening strength;

f_{ub} : Bolt yield strength;

A_s : Bolt diameter.

Table 2: Minimal values of pre-tightening in KN according to the bolts class (adapted of [11])

Bolt Class	Bolt Diameter (mm)							
	12	**16**	**20**	**22**	**24**	**27**	**30**	**36**
8.8	47	88	137	170	198	257	314	458
10.9	59	110	172	212	247	321	393	572

Torque Tightening

Tightening is ensured by a torque wrench, characterized by its easy calibration and operation. The process is divided in two phases: in the first one total stress is defined at 75% and a second phase where it is given 110% of total stress stipulated for the connection **[11]**.

This is the most common tightening method, due to its easy and quick execution. It is designated to bolt diameters inferior to 30mm. Its lack of precision can create important deviations between 20% and 60% of the stress **[12]**.

Pre-tightening deviation is determined by the equation:

$$\gamma = \frac{F_{0Max}}{F_{0Min}}$$ **[12]**

Where:

F_{0Max} : Maximal torque strength;

F_{0Min} : Minimal torque strength.

Tightening by Mechanical Elongation of the Bolt

Although the use of this kind of pre-tightening is uncommon, it can be used with that purpose. It is ensured by the tightening of a group of small bolts located around the nut.

The nut is tightened until the determined stress, followed by the tight of the small bolts. The stress against the surface of the plate is responsible for the pre-tightening of the bolt (Figure 26).

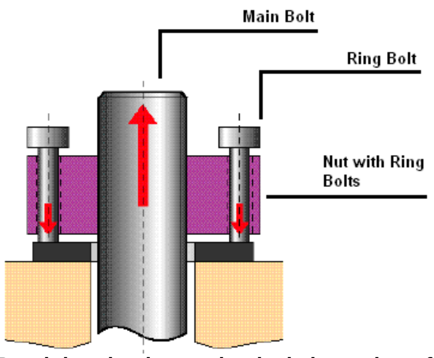

Figure 26: Pre-tightening by mechanical elongation of the bolt (adapted from [12])

This method has the highest precision of tightening. However it requires very specialized labour.

Tension Control Bolts

The bolt shaft is composed by the screw and a splined area. Fastening is executed by an electric wrench, composed by two coaxial axis. The inner axis fixes the shaft of the bolt in the splined area and the outside axis tight the nut. The rotation sense is opposite to each other. Fastening is completed when the shaft brakes by the union between the screw and the splined area. This torque stress provokes the elongation of the bolt **[13]**.

Hydraulic Pre-Tightening

It is the most used fastening method when pre-tightening has to be ensured. It consists in introducing an axial stress in the bolt by an hydraulic piston (Figure 27), provoking its elongation. Keeping the bolt stressed the nut is fastened. Pre-tightening eliminate residual stresses of torsion in the bolt.

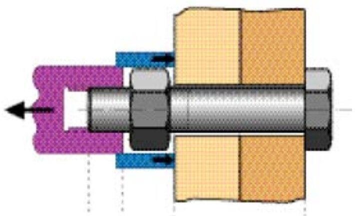

Figure 27: Hydraulic pre-tightening (adapted from [12])

The main characteristics of the process are presented:

- Quick and easy execution. It isn´t physical efforts by the operator, even for bolts with big dimensions;
- Method that can be applied to all kinds of bolts, with different diameters and dimensions;
- Can be executed in all kind of structural steels, including INOX steel and composite materials;
- The friction coefficient between the nut and the shaft is practically eliminated;
- Very satisfying Fastening precision, due to the hydraulic control of the process;

Concerning to Euro Tower building, bolt connections were executed in butt joints between beams and between columns, using diameters in a range from M4 to M64.

4.4.2. Execution Details of Welding Joints

The welding processes commonly used in the connections made on site are electrode welding and MIG/MAG welding. This is due to the versatility of these processes which allow difficult welding positions, such as vertical or overhead welding.

The most significant factor concerning on site welding is the weather conditions. These processes (electrode welding and MIG/MAG) are protected by a gas that surrounds the welding bath, allowing a proper deposition and cooling. The existence of wind and rain, particularly strong in height in the case of tall buildings can jeopardize the protection conferred by the gas. For this reason, it is common to protect the working platforms with side and top covers protecting the welder and the welding of high winds. In the Euro Tower building, in addition to the welding processes already mentioned, the cored wire welding was used eliminating the need of the protective gas, making it ideal for windy conditions and rain.

Moreover the temperature is a key factor of the quality of the welding, as its cooling requires a controlled environment that does not exist at a construction site. In fact, a sudden cooling of the welding can lead to higher values than the dimensional tolerances of the connection.

The integration of the assembly method and the possible welding processes in the execution planning of the welding is essential so that this process can be executed properly and with quality.

The welding procedure raises concerns regarding the health and safety of the operators, principles that should be taken into even more consideration in a construction site environment. Mainly:

- The welding debris which may be a danger to the welder or to workers in the vicinity;
- The welding equipments are very noisy, so welders should use hearing protection
- Welding, especially in tall buildings, is executed at high altitudes and in confined spaces. Safety against possible falls should be provided for the welders by protecting their work platform or by personal protection through a harness.
- Due to the use of welding helmets the perception of the surrounding environment by the welder is reduced, which can become a risk.

Whenever possible, welding connections must be performed at ground level and then be positioned in the structure. In this case study, this good practice was not possible to do because there was not enough room on the site to allow it. In this building, on site welds were butt connections at the bottom of columns. Other welding connections are the connection plates between braces and beams and welding between beams and columns (Figure 28).

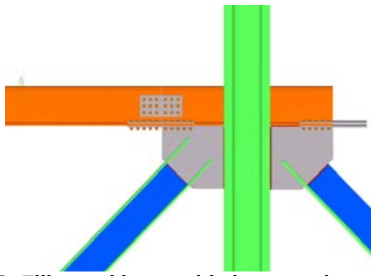

Figure 28: Fillet and butt welds between braces and connection plates to beam-column system

4.5. Statistic Analysis of Anomalies

Welding inspection was executed to braces, columns and reinforcement plates of braces and columns.

Inspection methods consisted in magnetic particle test for fillet welds and ultrasonic test for butt welds.

Acceptation criteria is defined in contractor specification that determines the rejection of any discontinuities detected on total weld thickness

a. Braces

Table 3: Number of tests executed in braces, regarding welding type

	Welding type			Total
	Fillet weld	Butt Weld	Fillet and Butt weld	
Nº of tests	243	0	189	432
% of tests	56		44	

The welding joints inspected were corner joint and corner and butt joint between braces and connection plates to beam-column system (Figure 29) and to beams (Figure 30)

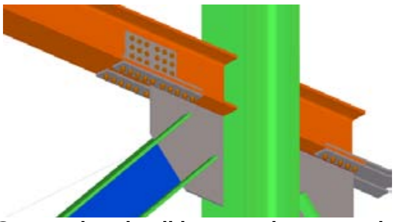

Figure 29: Connection detail between braces and connection plate to beam-column system

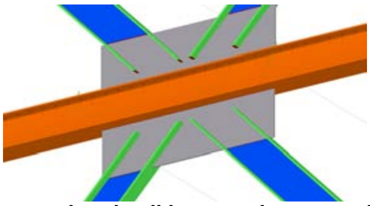

Figure 30: Connection detail between braces and connection plate to beams

The welding process used in brace connections were electrode welding, and inspection method magnetic particle.

Table 4: Magnetic particle Test results of fillet welds, in braces

	Test Result	
	Admissible Result	Non admissible Result
Nº of tests	239	3
% of tests	98.8	1.2

The same test was executed by fillet and butt welds. However its result was always admissible.

b. Columns

These structural elements are I composed sections and rectangular box sections. The connections tested were butt weld between columns and fillet welds between plates of box section (Figure 31) (Table 5).

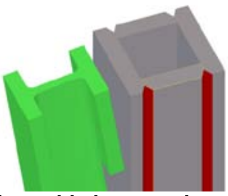

Figure 31: Fillet welds between box section plates

Table 5: Number of tests executed in columns, regarding welding types

	Welding Type		Total
	Fillet weld	Butt Weld	
Nº of tests	12	249	261
% of tests	5	95	

Table 6: Test results of Butt welds in columns

	Test Result	
	Admissible Result	Non admissible Result
Nº of tests	191	58
% of tests	77	23

Due to the number of butt welds tested, it is not possible to affirm that the lower percentage of non admissible tests is not significant, because the reparations that took place determined the development of assembly (Table 6).

The welding processes used in columns were cored wire welding (CWW) and MIG/MAG, which distribution is quantified in Table 7

Table 7: Number of tests executed in columns, regarding welding processes

	Welding Process		Total
	CWW	MIG/MAG	
Nº of tests	45	216	261
% of tests	17	83	

The tests executed show a bigger percentage of non admissible results for MIG/MAG welding, comparing to CWW (Table 8)

Table 8: Test results to MIG/MAG and CWW weldings, in columns

	Test Result	
	Admissible Result	Non admissible Result
MIG/MAG (%)	74	26
CWW (%)	96	4

These results can be justified by the better performance of cored wire welding in site environments, where wind is determinant for welding quality. Thus, these results confirm that this welding process is ideal for site conditions. However, the lack of specialized labour and its cost can be conditions hard to fulfill, so that its use it´s only justified in extreme cases. Furthermore, the distribution of welding processes (Table 9) corroborates this conclusion, because only a few numbers of welds were executed by CWW, in days that wind conditions make MIG/MAG impossible.

Table 9: Distribution of butt welds in columns, regarding welding process

	Welding Process in Butt welds		Total
	CWW	MIG/MAG	
Nº of tests	45	204	249
% of tests	18	82	

Ultrasonic test allows the lengthwise analysis of the anomaly. Figure 32 depicts the distribution of non admissible tests regarding anomaly gap lengths. It can be noticed that more than half of the anomalies have 250mm and 500mm length.

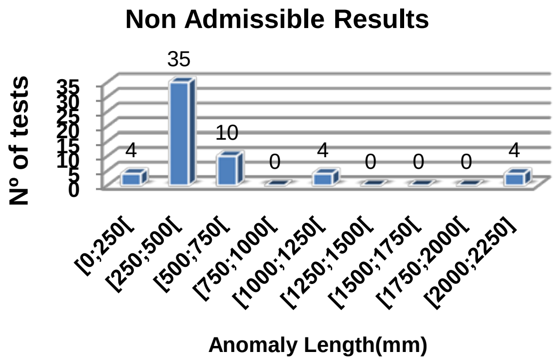

Figure 32: Distribution of non admissible tests, regarding anomaly length

Another result approach that allows knowing the lengthwise and transversal extension of the anomaly, comparing to the length and thickness of the welding is shown in Figure 33 and Figure 34.

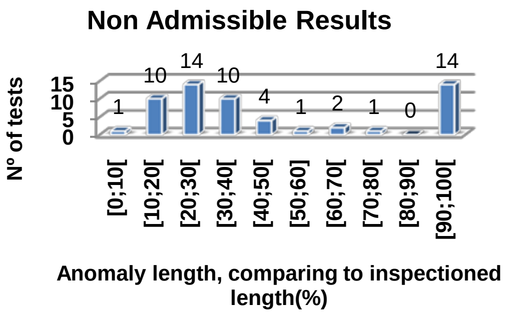

Figure 33: Distribution of non admissible results, regarding anomaly length

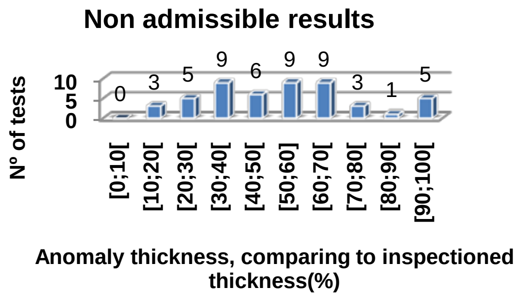

Figure 34: Distribution of non admissible results, regarding anomaly thickness

The results show that, concerning the anomaly length, in 60% of the cases, by 10 to 40% of the inspected length. Moreover, there are a considerable number (25%) that its inspected length presents full extension anomalies.

Concerning anomaly thickness, the results show that most of the tests (40%) revealed anomalies in a thickness between 30 to 70% of the inspected thickness. This analysis has a significant importance because it allows one to locate weld reparation requirement, permitting to reduce reparations time and costs. The reparation always consists in full removal of the non conform weld.

Concerning butt welds executed by MIG/MAG and CWW a distribution of results admissibility was executed, regarding if the weld butt joint is on flanges or on webs.

The percentages of non admissible results are similar (Figure 35 and Figure 36). This fact corroborates the evidences on site where the same level of cracking was detected.

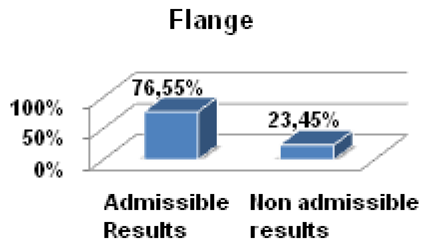

Figure 35: Tests results between butt welds executed between flanges

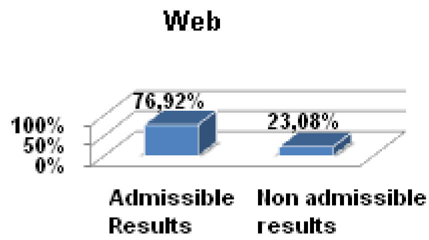

Figure 36: Tests results between butt welds executed between webs

5 Conclusions

All the structural solutions were characterized. The "Frame-wall" structural system presented a satisfactory seismic behaviour, with high mass participation in the first vibration modes, where torsion has a reduced influence. In the comparative analyses made to the actual standards several discrepancies were detected. This fact supports the importance of global application Standards, as Eurocodes.

The Civil Engineer´s knowledge of welding processes and its several variabilities used in steel construction is crucial for the correct execution on site. The analysis executed to Quality Control made in the workshop corroborates this fact. Welding, before and after shotblasting, is the manufacturing phase where more non conformities were reported. Documentation errors were also detected to be the main cause of the non conformities reported, which leads to higher reparation costs.

On site assembly was characterized, and described in its several stages, from assembly planning to foundation ground location and respective tolerances. Equipment planning is a very important task for site management, because it is essential to the accomplishment of defined assembly schedules.

The analysis executed to the quality control made to the site welding revealed that they are strongly determined by the surrounding environment. This fact is supported by the reduced number of anomalies reported in cored wire welding.

Thus, one may conclude that, in a Civil Engineering context and specifically in regards to the management of steel construction, site welding is a connection method that should be avoided. Although it is less expensive when compared to bolting, one incurs in higher costs in order to create the ideal conditions for its execution.

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