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Evaluation of the Construction Process in Reinforced Concrete Buildings: The Case of Lima, Peru in the 21st Century

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Abstract The maelstrom of construction in Lima, Peru, at the beginning of the 21st century brought with it many technological advances, but at the same time, many construction procedures that guaranteed structural quality were neglected. The research collects all the faults found during the manufacture of reinforced concrete elements in buildings, with the aim of analyzing their causes and consequences. At the same time, it proposes an alternative solution that complies with Peruvian regulations. The work involved visiting various construction sites in Lima and recording incorrect construction procedures. A search of photographic and oral sources was also carried out to supplement the database. The results revealed that the root of the problem lay in a lack of investment on the part of builders, since they did not have adequate equipment to manufacture the structural elements correctly. Another problem was the architectural design, which did not allow for sufficient clearance for installations and ended up compromising the masonry or reinforced concrete. It was concluded that the participation of all those involved in the project is necessary, and that it must be addressed from the planning, design, and execution phases in order to minimize errors and setbacks and obtain a quality product.

Keywords Reinforced Concrete, Construction Procedures, Apartment Housing

1. Introduction

The activity of building is as old as civilization itself. From the moment humans became sedentary, they needed shelter to protect themselves from extreme weather, wild animals, and even other members of their own species. The need to build a residence required the perfection of techniques and skills to make dwellings increasingly safer.

Many of the buildings of the past have been destroyed by the harshness of time, but those that were much better planned and executed survived the forces of nature and/or self-destruction due to the deterioration of their materials, or because they were attacked by an external factor and were not built with the best engineering.

An example of engineering in ancient times is the case of the Romans [1], where architectural monuments and pavements made of concrete from that period have been preserved; these constructions stand out because they have endured over time. During the Renaissance, all sciences were revived, and later, during the Industrial Revolution, all engineering techniques became massively used and innovative [2].

The global construction industry entered a new era with the advent of “Portland cement”, which enabled the construction of increasingly taller buildings [3], complemented by state-of-the-art additives to obtain special properties in concrete. The mass construction of buildings, bridges, tunnels, etc., was encouraged, leading to the creation of more artistic works. The case of collective housing projects has been an initiative in most countries, generally managed with subsidies or state financing, commonly referred to as “social housing.” In most cases, these plans have worked and have been an incentive for the private sector to invest and become more technologically advanced in this type of enterprise.

The construction industry in Peru experienced a period of rapid infrastructure development between 2001 and 2015, which led to the massive construction of buildings, mostly for collective housing [4]. It was a period when many aspects were integrated to move forward with all investments related to this sector, from land policies as an urban element to the facilities granted by financial institutions.

Up to the present, this construction activity continues but at a slower pace, and along with the speed with which these projects are developed, other problems arise during their execution [5]; these have a lot to do with the structural quality of the buildings, while there is an obsession with meeting delivery deadlines, and work protocols are neglected in the various tasks involved in construction work [6].

The basic and main structure used in most of these buildings is “reinforced concrete,” which features key elements such as columns, walls, beams, and slabs, as well as staircases.

The problems that arise are directly related to the loss of monolithism in structures, irregularities in their geometry, and contamination of the concrete. The cause of these problems is closely related to a lack of commitment and ignorance on the part of construction workers, as well as poor supervision. In many other cases, the poor condition of equipment and tools prevents the proper manufacture of structural elements. Figure 1 shows a worker collecting aggregate material to mix with the other components of the concrete, without realizing that he is also collecting contaminating material from the ground (fines), which will degrade the quality of the concrete.

Figure 1. Worker collecting aggregate material. Author's source

The objective of this research is to compile all the errors committed during the construction of reinforced concrete buildings, classify them in the most didactic way possible, so that it’s possible to analyze them, explain the causes, and warn about the consequences that all these procedures entail. As a source of information, we have used on-site records of construction procedures carried out informally in buildings in Lima, as well as photographic and oral records dating back to the beginning of this century, a period of abundant real estate projects for housing in Lima, the capital of Peru.

Likewise, the work complements and analyzes from a very particular perspective the results developed in the master's thesis of Lengua [7], presented at the Pontifical Catholic University of Peru.

Table 1 lists the most relevant projects that have been reviewed and registered, through which research material could be obtained.

Table 1. Relevant projects as a source of information

Project name	Built area (m²)	Execution time (months)	Most common mistakes
Parque San Martín	3952	18	Inefficient steel coating
Libertadores	3220	14	Damaged and defective formwork
Colmenares	1697	10	Concrete contamination
Barcelona	1700	10	Columns and slabs with empty spaces
Clement	3773	16	non-aligned vertical elements
Tradiciones	2438	12	Inefficient steel coating

2. Literature Review

The evolution of construction procedures is always a topic of study, and there is a wealth of literature related to techniques and new methods for simplifying processes without compromising quality. Currently, increasingly sophisticated tools are being used to anticipate potential problems, such as Open BIM and Python. Singh [8] uses these tools in the design of reinforced concrete slabs, achieving a 25% reduction in human error. In other similar cases, neural networks are used. Papadimitriou [9] used them to reduce future repair costs by preventing possible errors in construction procedures, including the demolition of buildings.

It must be recognized that most of these errors are human, whether in the design, construction, or commissioning phase. Galvão [10] analyzed the cause of these potential errors, first classifying them and then making a qualitative assessment of them, finding 49 errors, which were determined on the basis of the probability of their occurrence and the consequences they could generate.

Saberbein [11] analyzes quality management applied to a project, determining the errors that most commonly occur on site, such as accumulating steel in the cores between beams and columns, which would then produce voids in the concrete, or the dimensions of the structural elements not being compatible with the architectural plans, which leads to time being wasted in clarifying the details of the project. Among the strategies for avoiding errors, Saberbein used work protocols, in which each stage of the construction process is recorded, thus preventing work from being approved when it is not done properly.

In 2018, a study was conducted on the factors influencing concrete quality [12], for which a series of surveys were carried out among a population of engineers, architects, and technicians, evaluating parameters such as labor, machinery, materials, methods, and the environment. Labor was found to be the factor with the least influence, while the majority considered the environment to be the main cause of concrete failures. In second place were methods, which included technical supervision, quality testing, and supervision of the type of work. This research was conducted in Colombia, a country with construction characteristics and habits very similar to those of Peru, as a result of its economy and purchasing power.

The traditional method of manufacturing concrete structures began to be replaced by prefabricated elements, but even more so when new technologies were sought to mold these elements. Berger [13] analyzed the possibility of forming concrete with very thin reinforced concrete sheets, which allow buckling up to a certain limit and end up giving the concrete surface a curved shape. A triangular prototype with a 7-meter edge and a thickness of 4 centimeters was used for the test, while the preliminary analysis was based on finite elements with the help of specialized software. The experiment yielded favorable results, as the concrete sheet never failed, opening up new lines of research.

One of the controversies that arose during the construction phase is whether formwork works better when it is made of wood or metal, and this is because errors could be attributed either to the type of equipment used or to the skill of the workforce. Arapa [14] analyzed the predominant factors that differentiate wood formwork from metal formwork by comparing various parameters. He found that metal formwork required less training time and fewer personnel to execute, as the work was less artisanal and many of the formwork panels were prefabricated. Arapa evaluated three factors: integrity, safety, and completeness, in addition to other sub-parameters such as ease of transport and storage, quality of labor, assembly performance, equipment maintenance, etc. Metal formwork consistently received higher ratings, leading to the conclusion that construction procedures work better when technology is incorporated into their development.

In some ways, architecture also contributes to research, helping to detect errors during the construction phase. Although these errors may appear to be purely aesthetic, they can lead to structural failures that later require more serious repair work. Figueroa [15] studied the pathologies, causes, and possible solutions to the faults observed in architectural concrete, the most important of which were the absence of cement paste, contamination due to steel oxidation, cracks due to settlement, the collapse of vertical elements, and the asymmetry of manufactured structural elements. In the end, the solution and/or repair involved an engineering solution, and it was to be expected, as Figueroa stated, that the poor training of the operators, combined with the poor condition of the materials and equipment, was the main cause of these errors.

From the articles reviewed, it can be concluded that errors in construction processes stem from a lack of technology, whether in labor or equipment, as well as from the incorporation of materials that do not damage the final product, which are reinforced concrete elements. The methodology applied is based on this research to discern which strategies lead to better performance in the quality of a building project.

3. Materials and Methods

The observation and recording setting, as explained above, is the city of Metropolitan Lima, and the study population consists of reinforced concrete buildings constructed since the beginning of the 21st century.

On the other hand, the development of the research involves a preliminary classification of the elements to be evaluated, which is why we have chosen to divide the structure into three sections: foundations, vertical elements, and horizontal elements. In each of these sections, we have recorded (after observation) the most common errors that could later cause serious problems for the structures.

A basic aspect when detecting the problem is to make an adequate diagnosis that allows us to know what will happen to the analyzed element (if the error persists), which is very important in order to propose a solution using appropriate procedures.

The innovative aspect of this research lies in the fact that solutions are approached not only from a technical point of view, but also from a productivity perspective, as it is understood that construction processes are part of the overall project management, which involves schedules and budgets. Next, the systematic grouping of errors and alternative solutions leads to an orderly discussion of results, which allows conclusions to be drawn and opens up new lines of research.

3.1. Research Setting

During the first two decades of this century, there was rapid real estate development in Lima, which led to the development of new technologies in reinforced concrete, allowing for the construction of increasingly taller buildings for housing. It is precisely these structures that are being evaluated, given that the speed of the work has led to errors that are constantly repeated, many of which set a precedent for subsequent errors.

The common features of these buildings are that they are all 70% reinforced concrete (the rest is masonry), increasingly industrialized formwork has been used in all of them, most of the concrete has been purchased ready-made and very rarely manufactured on site, and in many cases, the steel was already purchased in the right dimensions and did not have to be prepared on site. The concrete pouring processes were carried out using work trains, so the procedures were practically mechanized, as the architecture was similar on all floors of the building. This, in turn, allowed personnel to be trained in less time, as they were doing "almost repetitive" work.

The type of buildings selected had a completion period of between 8 months and 2 years. It could not be less due to the installation of finishes, nor could it take longer due to sales commitments with customers. As for the contractors participating in the projects, they all used similar quality standards and protocols, so the errors recorded on site were also similar in this type of structure.

3.2. Structural Elements Subject to Evaluation

As mentioned in the previous section, the structural elements of reinforced concrete buildings have been divided into three components: foundation elements, vertical elements, and horizontal elements. Each of these components will be broken down into the structural elements that comprise it, which is where the construction procedure will be evaluated.

Table 2. Specific errors in construction procedures

Foundation Elements	• Continuous footing • Excessive accumulation of trench rock • Incorrect dimensions of the trench Stone • Footings • External forces due to the proximity of footings • Absence of "Concrete slab" under the footing
Vertical Elements	• Lack of monolithism in the composition of the elements • Manufacturing of shear walls in sections • Reduction in cross-section • Horizontal roughing of the shear walls • Reduction in the density of structural elements • Insufficient Steel cover • Misalignment of vertical elements
Horizontal Elements	• Steel beams outside the column core • Insufficient concrete cover of steel in beams • Manufacture of cambered beams in sections • Poor concrete cover of steel in slabs • Excessive placement of pipes in slabs • Overloading of finished slabs

Table 2 shows all the situations that arise during the manufacture of structural elements, and that will be subject to evaluation. First, the function of these elements within the structural assembly of the building will be described, then the situations in question (construction defects) will be addressed, with a description and explanation of the repercussions they have on the structure. In turn, possible manufacturing alternatives will be recommended in order to reduce the vulnerability of the building.

It is important to note that the procedures evaluated are basically those whose errors have the greatest impact during construction processes, and that the proposed solutions are framed within Peru's National Building Regulations (RNE) and the sub-regulations corresponding to each chapter and/or specialty.

3.3. Theoretical Analysis of the Elements Studied

The structural behavior of a reinforced concrete building depends on the coherent interaction between its different structural elements, each designed to fulfill a specific function within the resistant system.

From the foundations to the superstructure elements, the flow of gravitational and lateral loads is transmitted hierarchically to the ground, ensuring stability, strength, and serviceability. This study theoretically analyzes the structural behavior of six fundamental elements, which are also the subject of this research: continuous foundation of cyclopean concrete, reinforced concrete footings, reinforced concrete walls, reinforced concrete columns, reinforced concrete beams, and reinforced concrete slabs.

3.3.1. Continuous Foundation of Cyclopean Concrete

The continuous cyclopean concrete footing is a continuous surface foundation element, used mainly to transmit linear loads from load-bearing walls to the foundation soil; from a structural point of view, its behavior is based on the predominant work in compression, since cyclopean concrete lacks reinforcement and has a very limited resistance to tension. Theoretically, the continuous foundation acts as a means of diffusing stresses, reducing the pressure transmitted to the ground by increasing the contact area. The design aims to ensure that the stresses at the base do not exceed the allowable bearing capacity of the soil and that the resultant of the loads remains within the middle third of the section, avoiding the appearance of tensile stresses at the soil-foundation interface; likewise, its mass and rigidity contribute to limiting excessive deformations, provided that the supporting soil is relatively homogeneous. The proper functioning of the continuous foundation, therefore, depends on the compatibility between geometry, applied load, and geotechnical properties of the soil.

3.3.2. Reinforced Concrete Footings

Reinforced concrete footings are isolated or combined foundation elements, designed to support concentrated loads from columns. Unlike bicycle foundations, footings incorporate reinforcing steel, which allows them to resist bending and shear, as well as compression. From a theoretical perspective, the footing behaves like a plate supported on an elastic medium (the ground), subjected to contact pressures that balance the axial load and the moments transmitted by the column; thus, the concrete resists compressions, while the steel absorbs the tensile forces induced by bending. The distribution of pressures at the base depends on the eccentricity of the load, and the design seeks to avoid tensile stresses in the soil. In addition, the resistance to unidirectional shear and punching shear is verified, critical phenomena that can generate brittle failures if not properly controlled.

3.3.3. Reinforced Concrete Walls

Reinforced concrete walls play an essential structural role in resisting lateral loads, especially in seismic zones. Its behavior is characterized by a predominantly shear and flexural-compression response, depending on its slenderness and the type of stress. Theoretically, structural walls function as highly rigid vertical elements, capable of limiting lateral displacements and controlling derivatives; thus, under seismic or wind loads, they develop internal stress fields where the concrete works in compression and the steel in tension, forming strut and tie mechanisms; in slender walls, the behavior is dominated by bending, while in low walls, shear predominates. The proper distribution and amount of reinforcement ensures ductility, energy dissipation, and crack control, key aspects for structural performance.

3.3.4. Reinforced Concrete Columns

Reinforced concrete columns are vertical elements responsible for transmitting gravitational loads, and to a lesser extent, lateral loads to the foundation; their structural behavior is governed by the interaction between axial load and bending moment, a phenomenon known as flexural compression. From a theoretical point of view, columns work as compressed elements with possible eccentricities, which generate non-uniform stress distributions; thus, the concrete resists most of the compression, while the longitudinal steel contributes to both strength and ductility. Transverse reinforcement (stirrups) fulfills essential functions of confinement of the concrete, control of buckling of the longitudinal steel, and resistance to inelastic deformation. In seismic-resistant systems, columns must be designed to avoid brittle mechanisms, ensuring ductile behavior and an appropriate strength hierarchy relative to beams and walls.

3.3.5. Reinforced Concrete Beams

Reinforced concrete beams are horizontal elements responsible for receiving loads from slabs and transferring them to columns or walls; their structural behavior is dominated by bending, accompanied by shear stresses and, in some cases, torsion. Theoretically, under bending, the lower or upper fiber of the beam enters into tension according to the direction of the moment, this resistance being assumed by the reinforcing steel, while the concrete works in compression; the shear stress is assumed by the beam, thanks to the combination of the concrete and the stirrups, developing mechanisms of compressed struts and steel ties.

The appropriate relationship between stiffness, strength, and ductility allows beams to act as energy dissipating elements in earthquake-resistant systems, favoring the formation of plastic hinges in controlled zones.

3.3.6. Reinforced Concrete Slabs

Reinforced concrete slabs are two-dimensional elements that function as plates or diaphragms, responsible for supporting distributed loads and transmitting them to beams, walls, or columns; their structural behavior depends on their support system and geometry, and they can work in one or two directions. Theoretically, slabs resist bending through a field of positive and negative moments, where steel is placed in the tension zones. In addition to their resistance function against gravitational loads, slabs also play a fundamental role as rigid diaphragms, ensuring the correct distribution of lateral forces towards the vertical elements of the structural system, ensuring continuity and rigidity in their plane, which are essential to achieve a coherent overall behavior of the building.

The structural behavior of a reinforced concrete building is the result of the efficient interaction between its structural elements; thus, while the foundations guarantee the safe transfer of loads to the ground, the elements of the superstructure (walls, columns, beams and slabs) form a resistant system capable of withstanding gravitational and lateral actions. Theoretical analysis shows that each element fulfills a specific function, but its performance is only adequate when designed considering the compatibility of deformations, the resistance hierarchy, and the fundamental principles of structural mechanics; this comprehensive approach is essential to ensure safety, stability, and durability in civil construction works.

4. Results

This section will present the construction defects listed in Table 2 and propose technical alternatives for their resolution.

4.1. Foundation Elements

4.1.1. Continuous Footing

Continuous footings are made of cyclopean concrete, and depending on their mix ratio, they contain aggregates up to 10 inches in diameter, and together they achieve a strength of up to 100 kg/cm^2 (no more is required).

Although in most cases the project dosage is respected, this is not the case when placing the material in the field, which is why the following incorrect procedures are recorded, as seen below.

- Excessive accumulation of trench rock

According to the National Building Regulations (RNE), in Chapter E060 on Reinforced Concrete, Article 22.10.1.b states that trench stone, as an aggregate material, should only occupy a maximum of 30% of the total mixture volume [16], which is calibrated as the trench is filled. However, operators generally pile up the trench stone to such an extent that it ends up stacked on top of each other. Figure 2 shows part of the side of a house, where it is clear to see how the continuous foundation contains an excessive amount of trench stone.

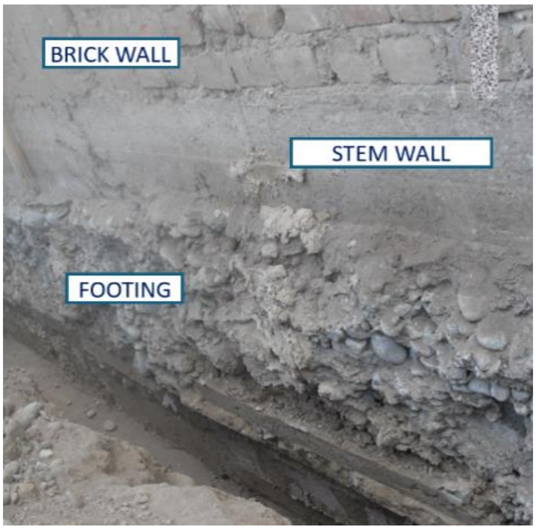

Figure 2. Accumulation of trench stones

The way to avoid this construction flaw is to calculate the volume of the trench where the concrete will be poured, and then take 30% of that volume to determine the total capacity of trench stones that will fit, which can be measured using wheelbarrows. It is important to note that operators must measure out the amount of stones they are going to place so that this measured volume can be distributed evenly throughout the trench.

- Incorrect dimensions of the trench stone

Cyclopean concrete is placed in excavations from 0.40 meters to 0.60 meters wide. This is not stipulated in RNE-E060, but it is the right amount of space for an operator to shape the terrain with freedom of movement. Therefore, RNE-E060, in Article 22.10.1.c, recommends that trench stones should not exceed 10 inches in diameter, and this is where a mistake is made, as stones larger than the permitted size are often placed. Figure 3 captures the moment when an operator receives the trench stones, and their excessive size can be seen, which in no way complies with the standards of the regulation.

Figure 3. Accumulation of ditch stones

The delivery of materials is always accompanied by a quality certificate, which indicates the characteristics of the material. Therefore, if a material does not meet the technical specifications, it must be rejected, and the responsibility must be assumed by the material supplier, as this also implies a delay in the project.

4.1.2. Footings

Footings are used to resist point loads on the structure, which can be isolated, combined, and used with central or eccentric loads. Below are some of the common errors.

- External forces due to the proximity of footings

When the footings exert pressure on the ground, a so-called “pressure bulb” is formed, the shape of which depends on the characteristics of the soil; The geotechnical study carried out on the soil prior to construction does not define the geometry of this bulb, so a more advanced study would have to be carried out if this were to be determined, and for the purposes of the project this would no longer be cost-effective, considering that the shape of the bulb could vary in different areas of the same terrain. To overcome this situation, soil mechanics theory is used. According to Das [17], the stress produced by a point load at 45 ° from the support level downwards is calculated by multiplying the load by a factor of “0.0844” and then dividing it by the square of the depth. This result would end up being very small. For this reason, for engineering design purposes, the soil space affected by the footing load is considered to be 45 ° downward (with respect to the horizontal line), measured from the edge of the footing base. Therefore, if any structural element is found in that projection, it will be affected by the load exerted by the footing.

As shown in Figure 4, the footing that is slightly lower is being affected, so there are two possible courses of action here. One would be to rethink the project and move one of the two footings, although this could go against the pre-established architecture. The other option would be to build a cyclopean concrete block beneath the footing that is slightly higher up, so that the projection of the pressure on the ground no longer intercepts any other structural element.

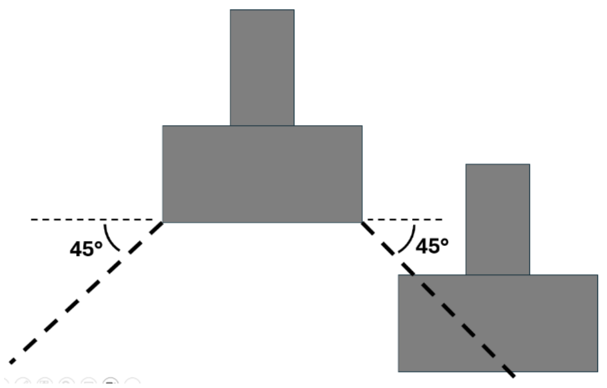

Figure 4. Impact of load projection between footings

- Absence of "Concrete slab" under the footing

The "screed" in foundations has no structural purpose. However, its presence serves to ensure that the footing and/or foundation being built does not come into contact with the ground when the mixture is poured, as otherwise the impact would cause the ground to break away and consequently contaminate the fresh concrete. Furthermore, as with all concrete elements, there must always be a covering between the concrete and the surface, and concrete blocks are placed directly on top of the screed to ensure that the steel in the footing does not come into contact with the outside during setting. In turn, the screed also serves for layout, since the steel that is placed prior to pouring the concrete must be well positioned, and for this, a clear and clean surface is needed.

Figure 5 shows the reinforcement of a footing, and the absence of flooring can be seen. In addition, coverings have been placed on top of the ground, which, due to the weight of the reinforcement itself, could sink, as they are acting as point loads, and there is a risk that the steel could come into contact with the raw earth.

Figure 5. Footing prior to pouring without screed

In Figure 5, it can be seen that the steel reinforcement has a considerable diameter, making it very difficult (almost impossible) to handle. Therefore, it will not offer any slack if, after pouring, it is not in the correct position according to the plans. This is precisely one of the purposes of the screed, to allow for greater precision when installing the steel, since the position of all the elements can be traced on that thin layer of concrete.

4.1.3. Construction Specifications about Design and Supervision

The main specification relates to the proper selection of personnel, both professional and technical (the crews assigned to each strategic point), where engineers and contracted personnel are required to have adequate experience and undergo continuous training. Supervision must not allow activities to continue without the corresponding written approval in the event of an error, as the processes are linked in each phase, requiring joint work; this helps to ensure that projects do not suffer losses or delays in the work schedule.

As for essential materials and elements, the work must have a supervisor who controls the requirements and arrival of materials, with the help of a control organization chart and inspection procedures. Next, it is the responsibility of the person in charge to verify that all materials (cement, aggregates, steel, among others) have quality certificates and tests that confirm that what was delivered complies with the technical specifications, as this will later cause problems in the execution and structure.

In general, the field study, which consists of the before, during, and after of each game played, requires greater emphasis and responsibility on the part of the engineer in charge, who must standardize processes and establish formal control points, preferably systemic, which are recorded in the project database to identify problems and propose immediate solutions during execution.

4.2. Vertical Elements

4.2.1. Lack of Monolithism in the Composition of the Elements

Reinforced concrete walls and columns are among the most important elements of a building's structure due to the rigidity they provide. For this reason, they must be manufactured in a single concrete pour, rather than in parts, as this would create so-called "cold joints," which are sections of concrete that are highly prone to structural failure. Below are some common mistakes that are made.

- Manufacturing of shear walls in sections

A concrete wall always has one side of its cross-section longer than the other, so the formwork work is usually more complicated than in columns, because when the concrete is poured, the element tends to lose its verticality. For this reason, walls are manufactured in stages, and sometimes they even wait more than 24 hours between stages, producing a single element sometimes with different types of concrete. Figure 6 shows the base of a concrete wall on the first floor, which was partially poured to be used as a guide for the rest of the wall, and you can see how it deteriorates in some parts while the surface becomes contaminated.

Figure 6. Partially poured concrete wall

The plane that separates concrete of different ages, since they were poured at different times, is called a "cold joint," and it is a potential failure surface if not properly treated, as it will always be exposed to contamination, and this is precisely what happens when a structural element is manufactured in stages.

In the case of very large walls, the formwork is more complex due to the number of accessories and props, and at the same time, the thrust of the material is much greater, so it is recommended to pour in stages, but with the same formwork and on the same day, to rule out the possibility of contamination of the concrete surface.

- Reduction in cross-section

This problem arises specifically when the formwork is damaged. For this reason, workers try to plug the holes with scraps of paper or other material, but in doing, so they reduce the cross-section of the vertical elements, since fresh concrete takes the shape of the mold, and when it encounters a foreign element, it leaves a void. Then, when the element is removed from the formwork after the concrete has hardened, an empty space has formed, and the workers proceed to fill it with low-quality structural mortar, thus losing the uniformity of the element's composition.

Figure 7 shows the bottom of the formwork for a column and how the wood, due to its poor condition, does not contribute to the tightness of the mold, so the workers have (erroneously) wedged in fragments of expanded polystyrene ("styrofoam"), which they will remove. Once the concrete has hardened, leaving a void, this would have already reduced the cross-section of the concrete. The workers mistakenly assume that by preparing a mixture of cement and sand, they can patch up the column, when in reality the element is no longer a monolithic structure.

Figure 7. Incorrect formwork procedure at the base of a column

4.2.2. Horizontal Roughing of the Shear Walls

Vertical elements are always in contact with horizontal elements, not necessarily at the ends; they can also intersect in the middle of the element. A very common example is stairs, where the steps and risers need to be embedded in the vertical wall. For this reason, workers first manufacture the wall, and then, once it has hardened, they cut it horizontally to anchor the steel. And this is precisely where they weaken the structural element.

Figure 8. Concrete walls next to the stair landing, roughly hewn horizontally

Figure 8 shows the walls next to the stair landing, which have had to be cut horizontally so that the concrete platform fits there once hardened. You can see that an adhesion bridge has been applied to the contact surface, which helps, but avoiding this practice would have yielded better results using other construction techniques.

The staircase is always built parallel to the slab, and although it may seem unusual, the concrete walls surrounding the staircase should be added to the concrete pour along with those horizontal elements. For the staircase and the walls around it, special formwork must be prepared specifically for that area, so that it can be moved from floor to floor as the building is erected. This arduous process will prevent "cold joints" and the loss of monolithism in the reinforced concrete walls.

4.2.3. Reduction in the Density of Structural Elements

In many buildings, the vertical elements are walls no more than 0.15 meters thick, and the design requires that the sanitary and electrical networks be embedded within them, which means that the pipes run inside the walls, and the same is true of the junction boxes. For this reason, the true density of the vertical concrete elements is lost.

For example, if you had a piece of solid wood in good condition, it would be very difficult to break it, but over time, the wood is affected by parasites that gradually degrade it until thin ducts form inside, which means that the piece of wood is no longer a solid element, but rather an element full of internal voids, and that is when it becomes easier to break. This example serves to explain what happens to concrete when it has many voids inside, generated by pipes and junction boxes, sanitary and electrical.

A clear example of this occurs when pipes belonging to electrical networks are often embedded in reinforced concrete walls, and since they must connect output points, they run horizontally for distances of up to 3 meters. Once the concrete is poured into the wall, the pipes create an internal groove, similar to making a horizontal cut after the concrete has hardened.

Figure 9 shows the reinforcement of a future reinforced concrete wall, where electrical outlets must be installed, fed through PVC pipes that run horizontally through the wall itself until they reach the point. This practice will generate an anticipated cut and also a reduction in the cross-section of the wall. It can even be seen that the wall is on the first floor, which creates more risk as these elements are responsible for supporting the load of the entire building.

In cases such as the one mentioned, the pipes (if they are very long) should run along the floor or slab and only enter the wall at the height of the electrical outlet.

Figure 9. PVC pipes installed incorrectly and horizontally within the reinforcement of a reinforced concrete wall

4.2.4. Poor Coating of Steel

Reinforced concrete elements have a failure development process. First, the concrete fails until it reaches the steel, which is when it begins to work. In fact, everything works together, which is why the cover distances required by the regulations must be respected. Figure 10 shows the reinforcement of a wall, completely touching the formwork panel. After pouring the concrete and removing the formwork, part of the steel will be exposed to the elements, which will cause it to react with oxygen and corrode in the near future. It must be clearly understood that any finish above the finished wall will not protect the steel from rust and corrosion, and it will eventually destroy the surrounding concrete.

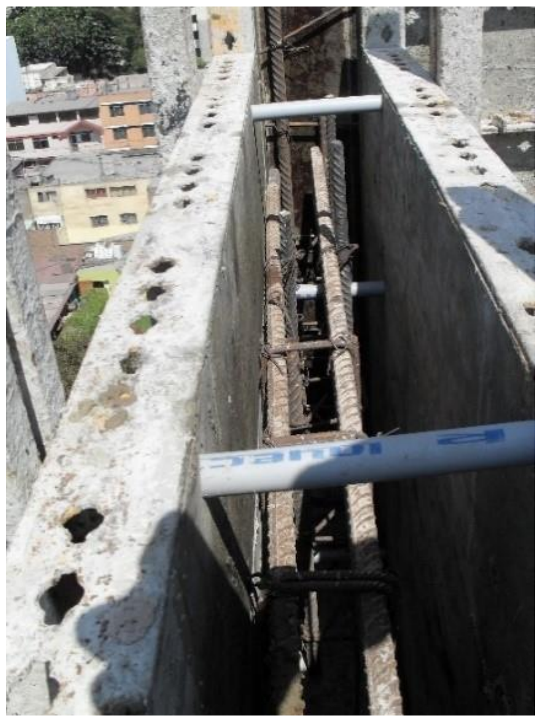

Figure 10. Steel reinforcement completely touching the formwork panel

The problem originates from the pouring of the horizontal element below the wall or column (it could be a footing or a slab). If the reinforcement of the vertical element is not in position, then it will be misplaced once the concrete has hardened, and when formwork is installed, the panels will be too close or too far from the steel. Another cause is simply the irresponsibility or ignorance of the operator in not ensuring that the steel maintains a distance from the formwork panels.

The best way to overcome this problem is to place prefabricated concrete elements between the steel and the formwork, which is the most recommended method, rather than using pieces of PVC pipe or small pieces of wood, which will ultimately only contaminate the concrete, as they are less resistant materials. There are polymer-based spacers on the market that are designed to attach to the steel without coming loose and achieve the required separation (see Figure 11).

Figure 11. Polymer-based spacer for the steel reinforcement of vertical concrete elements

4.2.5. Misalignment of Vertical Elements

When it comes to multi-story buildings, it is important to maintain the verticality of the structure, firstly to avoid eccentricities that generate any overload not foreseen in the design, and secondly because the problem will affect the finishes, which are expected to have a completely vertical surface, especially on the exterior, where a single plane can be seen from the first floor to the top floor. Elevator shafts could also be mentioned, since if the walls do not maintain the same verticality, the elevator car would not be able to move freely.

Figure 12 shows the structure of an elevator shaft, and how the walls of the openings that are repeated on each floor are not perfectly aligned with the same vertical line; the red line reveals the error.

This error is generated when the plumb line is based on the wall or column of the previous floor (below), since there is no certainty that it is perfectly vertical. Today's technology allows the use of more attractive instruments that provide greater precision, and above all, we work with axis lines as guides, which rise from the first floors along some of the walls on the edges of the interior ducts. These axes are redrawn on each roof slab, and from there, the lines of the plans are reproduced.

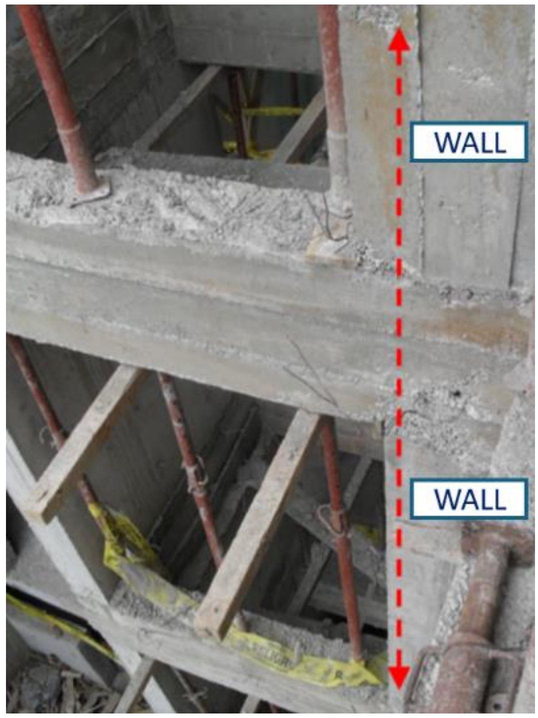

Figure 12. Structure that will house the elevator, with walls misaligned to the vertical

4.2.6. Construction Specifications about Design and Supervision

During the construction process, specifically in the execution of reinforced concrete elements, non-conformities are detected and recorded in the construction log, supervision report, or technical report, where the structural impact of the loss of monolithism due to cold joints, among other problems, is evaluated.

The engineer in charge is responsible for verifying the correct verticality, alignment, and adjustment of bolts before casting the different vertical elements. If these specifications are not met, a solution will be proposed on site, depending on the severity of the problem.

If the loss of section is significant, additional reinforcement will be evaluated according to the structural designer's criteria. Otherwise, the corrective measure will be to remove the defective concrete until a suitable material is reached, where the affected area is cleaned, and the bonding bridge is applied, followed by repair with structural repair mortar.

A similar solution will be applied to PVC pipes that have been incorrectly installed horizontally within the reinforcement of a reinforced concrete wall. Prior to pouring, it must be verified that the structural element is not interrupted by electrical or sanitary installations, recording these observations in the work logbook or raising non-conformities so that the position of these pipes can be changed. If the concrete has been poured without prior supervision and, upon verification, it does not comply with the structural design criteria or good practice standards, as it interferes with the resistant section and the minimum steel coverage, an immediate structural assessment by the designer and the definition of corrective measures will be ordered before continuing with the work, in order to guarantee the safety and load-bearing capacity of the structure.

4.3. Horizontal Elements

4.3.1. Steel Beams outside the Column Core

Horizontal structural elements rest on vertical structural elements, such as beams on columns, so it is understood that the core of the beams must be completely inserted into the core of the columns, so that the steel in the beams can develop its strength in a protected area away from the column's cover area, where it would be prone to concrete failure. See Figure 13, which shows the correct and incorrect ways of construction.

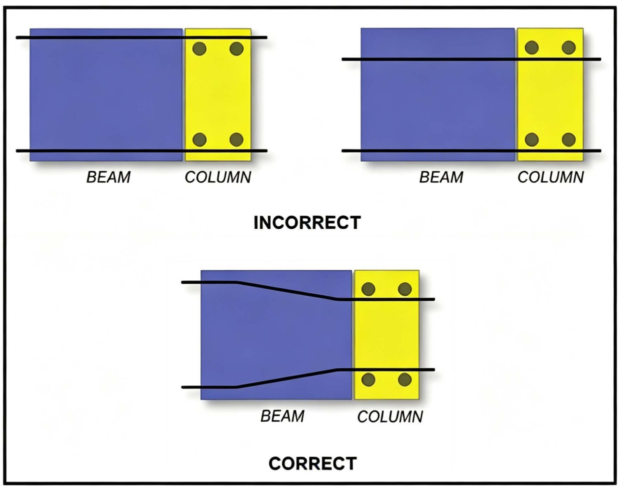

Figure 13. Various positions of steel beams within the core of the columns, viewed from above

The reason why operators install the iron outside the core of the column is that they want to avoid steel agglomeration, and to relieve congestion, they resort to this practice. This procedure could be validated, provided that there is a slab on the side where the steel of the beam exits the core, as this area would be much less exposed to early failure, and therefore the steel would remain protected; as is the case in Figure 14, where the steel of the beam does not completely enter the core of the column, but the entire node is located on a lightened slab.

Figure 14. Intersection of beam and column reinforcement

Finding an alternative solution is quite complex, as the architecture always predominates in the project, and it is not very feasible to widen columns so that the steel fits loosely. In situations like these, special concretes can be used, such as self-compacting concrete, which, due to its fluidity, will have no problem settling through the iron framework. If there is a slab on the side, one of the longitudinal steel bars of the beam could come out of the core of the column towards the side of the slab.

4.3.2. Insufficient Concrete Cover of Steel in Beams

One of the problems during construction, and continuing on from the previous section, is when there is a high density of steel in the cross-section of a beam, which leads to confusion about how to rearrange the steel bars without reducing the strength of the structural elements. In the case of a beam, when the steel bars are very close together, there is a risk that, during concrete pouring, the aggregates will not pass between the bars and may even block the concrete inlet, resulting in the formation of voids within the slab, which minimizes the quality of the rigid diaphragm (see Figure 15).

Figure 15. Reinforcement congestion in a beam frame

When this type of situation occurs, it is recommended to move some of the bars to a second row below, so that the steel can develop adhesion and the concrete is not prevented from passing between the bars. In the case of urban infrastructure, the concrete that is manufactured contains aggregates up to 3/4 inch in size; therefore, a minimum separation of one inch between bars must be sought. This is endorsed by RNE-E060 (Standard E-060 on Reinforced Concrete) of the National Building Regulations, which states in Article 7.6.1 that the minimum clear distance between parallel bars in a layer must be no less than the diameter of the bar, but never less than 25 millimeters [18].

4.3.3. Manufacture of Cambered Beams in Sections

The cambered beams in a slab serve to increase rigidity due to the inertia of one side of their cross-section. Therefore, they must be manufactured as a monolithic element, together with the slab, and in most cases, this is the case. The exception is when the camber of the beams is upward. This occurs in cambered beams that go to the edge of a duct, since the protruding part is combined with a wall, and the ceiling of the floor above is left completely flat.

Using formwork to create a mold that generates upward camber is somewhat complicated, as it is difficult to secure the moldings. To avoid this work, the operators pour the slab at the same level, leaving part of the cambered beam reinforcement exposed. Once the slab had hardened, they proceeded with the second part, which was to install the formwork over the exposed reinforcement to achieve the geometry of the remaining part of the beam (see Figure 16).

Figure 16. Reinforcement of an unfinished cambered beam

Concrete is a material that hardens over time, and when a structural element is manufactured in two parts, it has a tendency to adhere. However, it will never be the same as manufacturing it monolithically, but the problem that arises is even more complicated. The work is subject to a schedule, and after pouring a slab (with the half-cambered beam), the vertical elements (walls and columns) are installed, and the remaining part of the cambered beam is left for the end of the construction phase, with the aim of completing the remaining cambered beams on all floors in a single pour.

The aforementioned practice results in contamination of the contact surface between concrete of different ages, making it more difficult for them to bond and even hindering the work of any bonding bridge, if used.

There are two stages to solving this problem. The first is to consider the extra time involved in formwork for the cambered beam, so that it can be completed when the entire slab is poured. This way, the work will not be postponed until later and will not affect the schedule, as it will be included in it. Secondly, placing formwork vertically on top of a slab that has just been poured with fresh concrete may not be such a difficult task if these formwork panels are attached to the slab formwork with concrete blocks prior to pouring. This way, the fresh concrete will not be contaminated, and the option of attaching these formwork panels with wire alone is ruled out, as after setting, they may not be removed, thus promoting oxidation.

4.3.4. Poor Concrete Cover of Steel in Slabs

According to slab structure plans, steel always has a coating to develop adhesive strength. However, this rule is perhaps most often neglected in slabs, firstly because of the amount of steel they contain, and secondly because they are a transit area for workers. The consequence of the steel not ending up in its original position, according to the plans, is that the slab does not develop the design stresses, and in the future cracks will begin to appear that will eventually lead to oxidation of the reinforcing steel.

In the case of a solid slab, the steel tends to bend under the weight of workers' footsteps (see Figure 17). Therefore, it is necessary to place steel stops in the middle of the reinforcement. When the slab is lightened, traffic becomes easier, as there are ceiling bricks, but in the same way, due to the footsteps of the workers, the steel ends up sticking to the bricks, and the iron coating disappears (see Figure 18). In these cases, it is recommended to place concrete blocks under the steel bars to act as spacers.

Figure 17. Negative slab steel, arched by the passage of workers

Figure 18. View from beneath a lightweight slab

The lightweight slab has other drawbacks, as joists must be formed within the slab, separated by ceiling bricks, and if these bricks are not properly secured to the formwork, they will end up moving during pouring and spoil the geometry of the joists. Figure 18 shows how the joists of a lightweight slab were left, without any geometric shape or covering, and completely exposed. This situation can be resolved by simply fixing the bricks to the formwork, using steel nails as stops (see Figure 19). A more practical way to solve this problem would also be to use prefabricated joists.

Figure 19. Method for fixing ceiling bricks

4.3.5. Excessive Placement of Pipes in Slabs

As mentioned above in relation to vertical elements, excess piping in slabs also reduces the density of these elements, meaning that they will not perform as expected in the design and will not respond accurately to the stresses to which they are subjected. Figure 20 shows a lightweight slab with excessive agglomeration of a network of communication pipes, due to the fact that the design requires an outlet box there. However, this area becomes a potential point of failure, especially because the junction where the pipes are concentrated is located above a beam that is important for the slab. In Figure 21, drainage pipes cross a cambered beam, reducing its load-bearing capacity, which is quite detrimental, since the beam in question is supporting a section of the lightweight slab.

Figure 20. Clustering of pipes in a solid slab

Figure 21. Wall-mounted drain battery

The maximum thickness of a slab in Peru is 0.30 meters, which is sufficient to install a drainage system without any problems, except that it will prevent the formation of some beams or joists in advance, and in the case of a solid slab, it is similar. The main reason behind this practice is that architectural designs for buildings in Peru rarely include a separate space for pipes, as this would mean making the floors slightly higher, which would lead to budget changes.

For the reasons outlined above, pipes suspended from the ceiling represent an alternative solution. This avoids having to damage the slab and, furthermore, if repairs are required, they would be easier to carry out, as all the pipes are visible and there would be no need to break the slab beforehand. Another alternative solution would be to increase the thickness of the slab, but this would increase costs and the weight of the structure, and therefore require more steel reinforcement.

4.3.6. Overloading on Finished Slabs

Reinforced concrete slabs, whether solid or lightweight, are designed to support an additional load on top of their own weight. This will come into play once the building is in use. However, during the construction phase, materials are often stored on each of the newly completed slabs, distributed across the different floors depending on requirements. These materials may include bricks, bags of cement, boxes of ceramic tiles, sand, etc. See Figures 22 and 23.

Figure 22. Excess ceiling bricks piled up on a slab

Figure 23. Construction materials accumulated on the construction site

According to Standard E-020 (Loads) of the National Building Regulations, slabs must withstand a maximum of 300 kg per square meter indoors, and if a typical room in a home is 20 square meters, the space would only withstand 6,000 kg, but the accumulation of material and/or debris often exceeds this number. The aforementioned loads are not sufficient to cause the slab to collapse, as the design takes safety factors into account, but microcracks are generated, which are not visible at first. As the years go by, these cracks become increasingly noticeable until the steel embedded in the concrete comes into contact with oxygen. This is where oxidation and then corrosion of the steel occur, causing the surrounding concrete to flake and fall off, thus deteriorating the slab.

The only way to avoid this overload on the slab is with good planning. First, only bring up the material that will be used that day, then have the necessary equipment for vertical transport (elevators, winches, crane towers, etc.), and finally, finish the work that was scheduled for the day, as this also prevents the unnecessary accumulation of material and/or equipment on the slab. Likewise, waste produced as a result of work must have a designated route for disposal, so that it does not create disorder or cause specific loads on the floors.

4.3.7. Construction Specifications about Design and Supervision

During the execution of a project, various problems arise in the different construction processes, since during the design stage, structural configurations and construction details are defined under ideal conditions, while in the execution stage, the project is carried out under real conditions and various factors.

There are situations where the steel reinforcement of beams or the connection between beams and columns exceeds the defined dimensions. In these cases, the use of special concrete, as well as modifications to the steel reinforcement in coordination with specialists, allows for the correct pouring of concrete into the beams and connections between elements, ensuring proper adhesion between materials, connections, and functionality of the elements. Proper supervision of formwork, steel reinforcement, and concrete pouring in horizontal reinforced concrete elements prevents deflections, misplacement, and disorder of materials, resulting in the proper execution of reinforced concrete elements. Preventing the saturation of pipes in structural elements such as slabs allows for correct design behavior, which is why, in some cases, it is decided to separate these elements, respecting the regulations and theoretical conditions for their correct tasks.

Proper planning allows us to stockpile the materials needed for each construction activity while respecting structurally designed spaces and without altering their strength and functions, even if they were executed in a short or medium time frame. Coordination with specialists and the search for new resources, plus adequate supervision in decision-making and good planning, will allow us to move forward with the project without altering the functionality of its building elements.

5. Discussion of Results

The investigation revealed, on the one hand, the mistakes made during the construction process, but at the same time, it generated solutions to counteract and anticipate them. The discussion of results will focus on two aspects: technical and productive, and in each of these, the causes that gave rise to them will be highlighted, as well as the context of the events.

- From a technical standpoint:

The assessment addressed three issues: the loss of monolithism in structures, irregularities in their geometry, and the contamination to which concrete is exposed, considering that the guidelines for good practices are found in the National Building Regulations.

Monolithic structures prevent the appearance of "cold joints" (mentioned above) and avoid the formation of potential failure zones, which would be ideal; Torres et al. [19] subjected a group of cylindrical test specimens to axial compression. One sample from the group was cast in two parts, so that cold joints were induced diagonally and horizontally. The results showed that the test specimens in which no cold joints were induced were those that exhibited the greatest resistance. It is easier to pour concrete monolithically in horizontal elements, since their molding involves vertical shoring that does not exceed three meters in height, and these accessories are easy to obtain and/or rent.

The problem lies with the vertical elements, since after pouring concrete, care must be taken to ensure that they do not lose their intended balance. This is why struts are placed at an angle, so that the element does not tend to lean to one side; it should be noted that due to its height, concrete generates a lot of pressure, since even when fresh, it behaves like a fluid, and the thrust force of the concrete tilts the formwork. This is why very tall vertical elements are often built in stages. Domsa and Catinas [20] studied the effect of concrete pressure on formwork using different pouring speeds (height/time) and determined that both variables were directly proportional. However, at pouring speeds of 4 meters/hour or higher, the maximum resistance on the panels remained almost constant. This is because concrete setting is independent and does not depend on the pouring speed; in practice, this criterion can be used to eliminate cold joints and achieve monolithic pouring.

With regard to irregularities in the geometry of structural elements, whether due to pipe networks embedded in the concrete or poor formwork, this means that there is an area where the concrete will not develop its full strength, as the cross-sectional area has been reduced; it is likely that a single one of these faults will not affect the behavior of the structure as a whole, as there will be other (very well-manufactured) elements that will compensate for these deficiencies. However, the difficulty arises when many of these errors occur, as there are then fewer elements left to compensate for the rigidity of the structure. For this reason, RNE-E060 (Standard E-060 on Reinforced Concrete) always includes a safety factor in the design, even though in practice it is not advisable to use it. The effect caused by the inclusion of pipes in horizontal structural elements has led to various experiments. Ampaire [21] carried out a virtual simulation, while Fonseca and Suarez [22] experimented with real specimens. In both cases, they concluded that the diameter of the pipes and their position within the element affected its strength, stiffness, and ductility; this construction flaw is common in buildings with very limited architectural space.

Contamination of concrete is a common mistake when it is manufactured on site, and is usually due to improper storage of materials. As mentioned above, for practical reasons on site, materials are stored in places where they are much easier to retrieve for tasks, and this causes the material to travel from one place to another, picking up different types of waste each time; concrete can only allow the inclusion of foreign elements up to a certain proportion, which is difficult to measure during construction, so these elements filter through without being detected by the human eye, and the consequences begin to be seen in the medium and long term, which is very harmful to the building.

- From a production standpoint:

The responsibility with which a building is constructed must be maintained under the same standards worldwide, as it is a space that will house human lives. Since the early years of the 21st century, there has been a high demand for building construction (in Lima), and all engineering projects have been subject to deadlines, which are subject to financial penalties if not met.

Compliance with schedules is an important factor to consider, and poor planning from the outset of projects is what leads to errors. Currently, and for several years now, new work philosophies have been implemented, such as "Lean Construction" [23], which, if well managed, guarantees productivity and quality in construction projects. In the cases studied, for example, if there was no adequate coating on the structural elements, it was because the right personnel were not brought in to carry out the work, and the site foreman did not fully comply with the plans. Furthermore, there was no adequate monitoring by the supervisors or the field engineer; in other words, there were many people responsible, and they were all focused solely on meeting the schedule, since the economic success of their project depended on it. The lack of certain tools, equipment, or accessories must be controlled by Unit Price Analysis, which specifies what the contractor is considering for the work (those items included in the budget); otherwise, any of the tasks to be performed will not be of the required quality.

Finding excellence in construction procedures involves merging all areas of the project. In this case, quality must be combined with productivity, so the schedule must be drawn up according to the needs of each task. Each operator will then perform their role based on the indicated protocols, and at the same time, workers must feel motivated in their jobs. Coronel et al. [24] mention that lower performance on the job comes from personnel with lower salaries and less education. This was corroborated by their working conditions and the little training they received, leading to the conclusion that attitude at work is directly proportional to working conditions and, therefore, becomes a formula for improving productivity on the job.

6. Conclusions

The research was conducted in Lima in the present century, so the vices found correspond to the habits of Lima workers, under the climatic and logistical conditions of that city.

The characteristics of multi-family housing architecture in Lima (in recent decades) mean that structural design must take into account reinforcements that are somewhat complicated to install, such as slender walls or narrow beams, which means that the formwork for these elements must be forced during construction, and then special additives must be considered during concrete pouring. Likewise, the excessive amount of piping embedded in the walls and slabs is due to the fact that there is no clearance beyond the dimensions of the structural elements. The demand for housing in Lima, with its very high population, means that spaces (including air spaces) must be used to their full potential. For this reason, a few centimeters are extremely valuable in architectural design, which is why the performance of structural elements is sacrificed, reducing their volume. The cases presented in this research are a fairly representative sample of the bad habits incurred by workers in the initial stage during the reinforced concrete phase, which is the most important part of the building, as it will determine the structural behavior in the event of seismic events. Therefore, it is necessary that the management of such large-scale projects be approached from many angles, including quality, costs, deadlines, safety, and the environment. Communication and coordination among all those involved in the project are necessary to achieve optimal results. Based on the above, there is no situation that cannot be resolved with the technological tools currently available; the regulations that support these solutions and modern management applications, such as the use of statistical methods: Pareto chart, Statistical Process Control (SPC), statistical performance indicators, among others. Through research techniques (observation, identification, and data collection), the types of errors to be analyzed are defined, quantified, and subsequently used to generate trends and patterns that are repetitive in various construction processes. This allows for anticipation before activities are carried out, reducing rework and optimizing the use of resources, thereby strengthening quality control and improving projects. Currently, the integration of the aforementioned methodology with the "Lean Construction" approach allows for the objective evaluation of construction processes, identifying sources of variability and proposing improvements aimed at reducing waste and increasing efficiency in reinforced concrete buildings. The application of theories and concepts under the policies used in engineering, and a responsible attitude towards those carrying out all tasks in a civil construction project, ensure high-quality, safe, and durable buildings.

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