Structural design of the new Sørlandets Kunstmuseum, Kristiansand – Rehabilitation of 1930s concrete silos

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RESUMEN

La rehabilitación de los silos de grano construidos entre 1935 y 1939, junto con los nuevos volúmenes alrededor de los mismos, forman el nuevo museo en Odderøya. La propuesta arquitectónica es crear una gran área diáfana para exposiciones, Silo Hall a partir de la demolición de parte de los silos por bajo del nivel 5. Además, se construirá un nuevo espacio de restauración ubicado en los pisos superiores de la estructura. El principal desafío estructural aparece en las fases de rehabilitación, demolición de parte de los silos, y el refuerzo de nuevas "super columnas" de las partes restantes de las paredes de los silos.

ABSTRACT

The rehabilitation of the grain silos built between 1935 and 1939, together with the new buildings around them, form the new Sørlandets Kunstmuseum in Odderøya. The architectural proposal is to create an impressive, open exhibition area, the Silo Hall, by demolishing extensively the cylindrical silos below level 5. Major structural challenges include the demolition, repair and strengthening of the silos and the creation of new "super columns" based on the remaining parts of the silo walls.

PALABRAS CLAVE: Rehabilitación, Hormigón Armado, Silo, membrana
KEYWORDS: Rehabilitation, Reinforced concrete, Silo, membranes.

1. Description of the project. Architectural vision

The Kunstsilo project is a rehabilitation and transformation of the old grain silos located at Odderøya in Kristiansand (Norway) into a contemporary art museum. The original silos, designed in 1935, have an architectural and patrimonial value, but are currently in decay and will not survive without a new use. The building is located today next to the Kilden Performing Arts Centre and is to become a part of Kristiansand´s new cultural quarter with strong regional ambitions.

1.1. Existing building

The existing silo construction can be divided in three parts according to the time of their construction: original silos from 1935, silos extension from 1939 and annex north extension from 1996. The main volume is formed by the old battery of 3x10 reinforced concrete silos, with a height of 38m, an interior diameter of 4.40m per cylinder and a thickness of the concrete walls of 150mm.

The silos are supported on reinforced concrete columns at the first floor to provide access under the silos. There is an expansion joint between the 1935 and 1939 buildings. The annex building facing towards the sea (west side), and the existing north extension, will be demolished for the new project.

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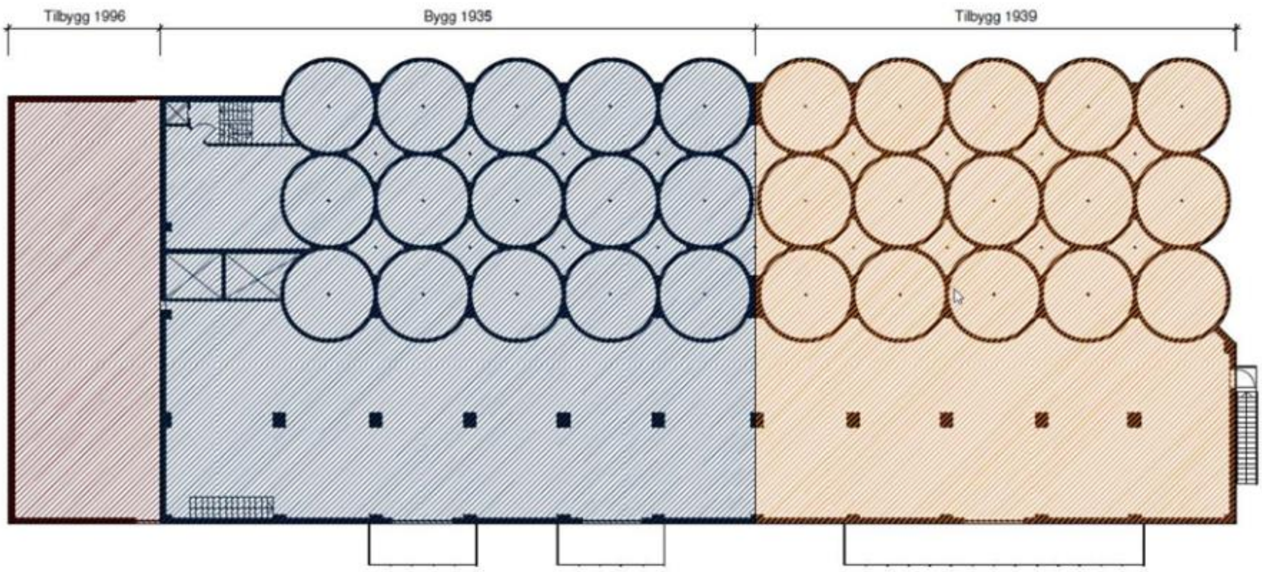

Figure 1. Plan of the existing silos built over different years..

1.2. Architectural vision. New Building

The new project proposal by architects Mestres Wåge, BAX studio and Mendoza Partida was chosen as the competition winner due to its simple and powerful strategy for the redesign of the silo in accordance with its new function. By making some cuts into the interior of the silos a monumental volume is opened up to create an impressive exhibition area that gives the future museum a strong and unique character.

Figure 2. Renderings of the renovated building as projected. Internal longitudinal cut and external view.

The new building will consist of three volumes: the central part occupied by the silos, the volume at the west side and the new annex building at the east side.

The biggest impact on the structure from the architectural proposal is the large exhibition area (silo hall) that requires the demolition of most of the cylindrical silos from level 5 downwards to create a large open exhibition space. The exhibition floors are to have large spans without columns. The following images illustrate the new building proposal.

2. Study of alternatives for the structural system

During the concept design process different alternatives were studied for the support of the silos structure following aspects such as reliability, redundancy, compatible with construction sequence or respect of the architectural requirements.

2.1. Alternative 1: Silos acting as a deep beam

The concept behind this option is to make the silos to work as a deep transfer beam. This is to assume, and to analyse the possibility that, once the silos bottom has been cut, the remaining part will act as vertical diaphragm that would be able to transfer the loads to the super columns (silos left without being cut). This option takes benefit from the stiffness of the silos structure, but to act as a proper deep beam, horizontal diaphragms are to be introduced at the top and bottom of the silos. To do so, strategically located radial steel structures are envisaged, to be placed at top and bottom of the silos, as well as concrete diaphragms within the rhomboid shaped spaces available between the silos.

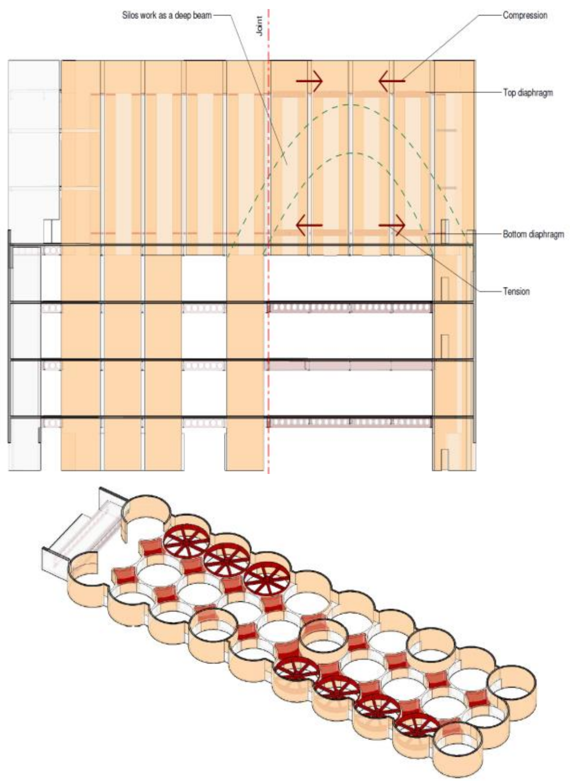

Figure 3. Alternative 1: Silos acting as a deep beam

2.2 Alternative 2: Two-Level-Transfer Structures

This option is conceptually based on hanging the silos from stiff trusses located at roof level. These trusses will transfer the load towards the perimeter, where new embedded concrete columns will be provided in the space available between silos. These new columns dimensions will be defined not to compromise the silos outline aesthetics.

A second transfer structure is provided at level 5using large RC beams spanning between super columns (silos not demolished) taking the loads from the new embedded perimeter columns. The super columns will include those silos that are not cut at fifth floor (although they will be partially demolished) strengthened by a new concrete outer layer. This will increase their stiffness against buckling, as well taking the heavy point loads from the concrete RC transfer beams.

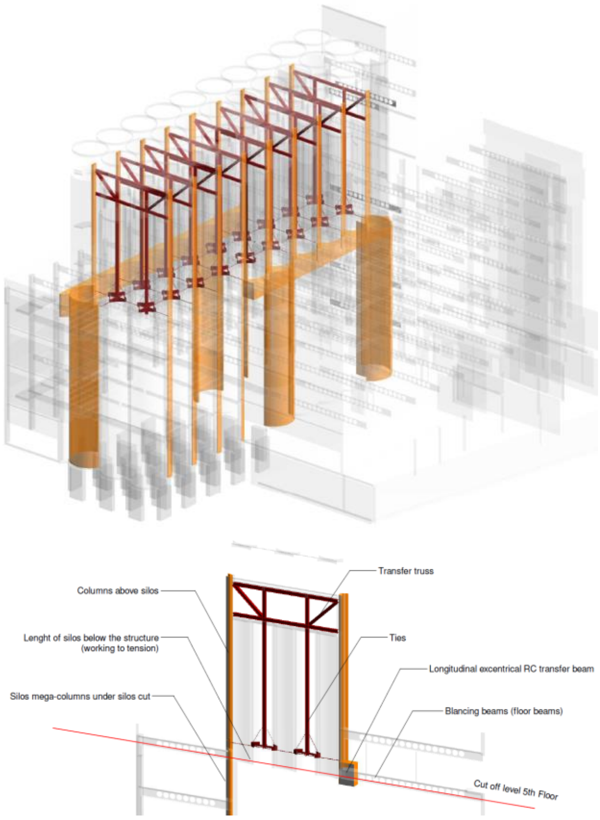

Figure 4. Alternative 2: Two-Level-Transfer Structures

2.3 Alternative 3: Roof steel transfer structure

The structural principles of this solution are based on providing all the transfer structure at roof level. This solution would propose a system of spatial transfer trusses that would take the load of the silos to the super columns that would start at roof level. However, the stiffness of this structure is much lower than the silos which leads to an inefficient system. Therefore, no further analysis was developed.

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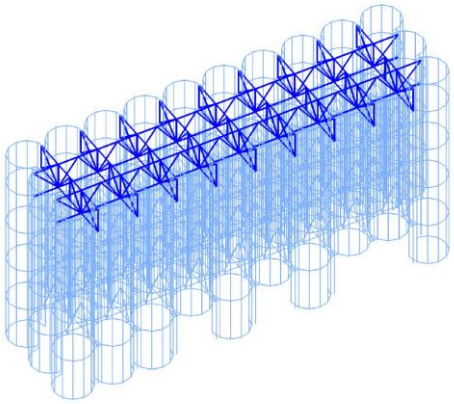

Figure 5. Alternative 3: Roof steel transfer structure

2.4 Alternative 4: Additional half silo acting as a new support and diaphragm at cut level.

This option is conceptually based on the silos as the main structural system. To provide stability, it is proposed to add an extra support from that conceived by the architects. Furthermore, the cut level is reinforced by adding a diaphragm which connects all silos while keeps the holes visible from below. The lateral RC beams are placed to ensure a collaborative vertical behaviour.

The final solution is based on keeping the joint between silos disconnected. Therefore, there are two separate structures with different behaviour. The 1939 silos have a much more flexible response.

Several additional analyses were performed with different alternatives for the joint. However, the design team established a premise to try to minimise the impact on the existing structure. That is the reason why alternative 4 was the preferred one for all the disciplines involved.

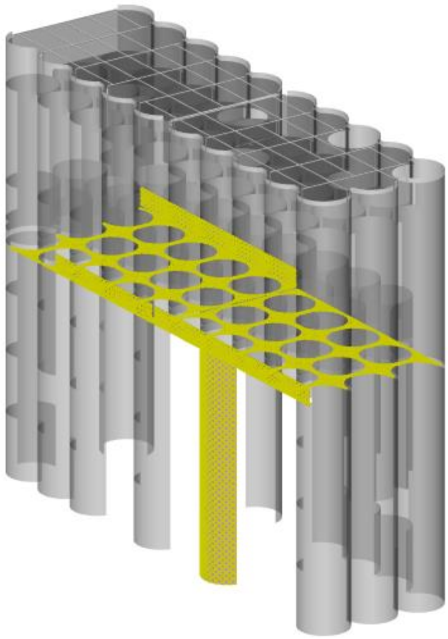

Figure 6. Alternative 4: Additional support and diaphragm

3. Structural Concept

The joint between the 1935 and 1939 silo blocks is kept as a structural joint in the rehabilitated building above ground, separating thus into two separate structures as shown in the figure below. Each of those structures would then consist of a part which is purely singular, the rehabilitated silos, i.e. structures conceived as silos that will now be driven to work very differently, and the standard buildings to the east and west. All will rest on foundations to be built while maintaining the stability of the existing silo structures.

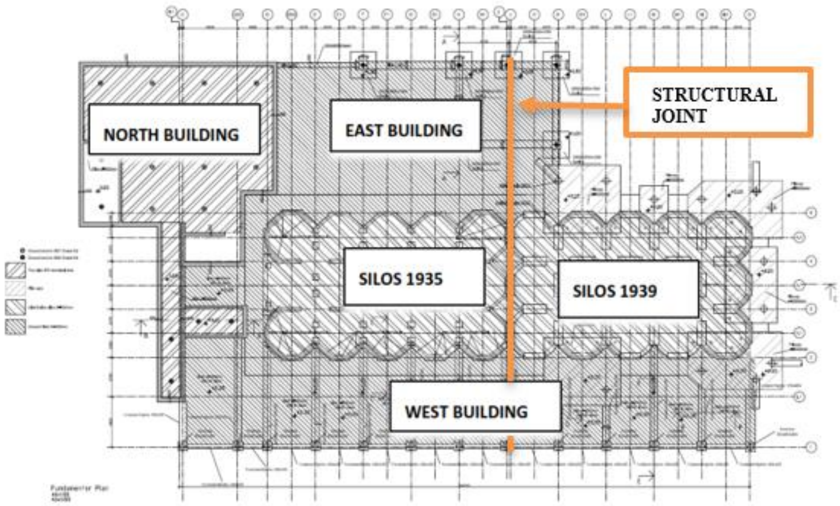

Figure 7. Plan distribution of different buildings at the renovation project.

3.1 Silos Buildings –Two independent structures separated by the existing joint.

The concept is based on creating a deep transfer beam with the silos above the cut level.

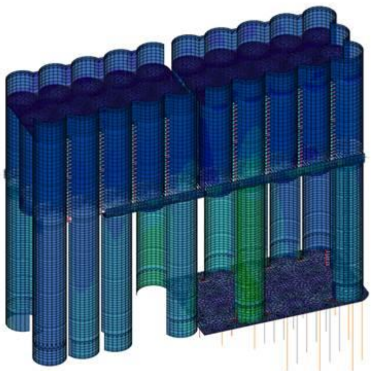

Figure 8. F.E.M. view.

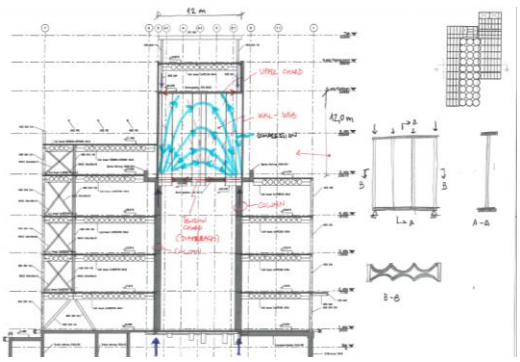

Figure 9. Structural scheme in a transverse cut of silos

This is to assume, and to analyse, the possibility that, once the bottom of the silos has been cut, the remaining part will act as vertical diaphragm, able to transfer the loads to the supercolumns (silos left without being cut). This benefits from the stiffness of the silos structure, but in order to act as a proper deep beam, horizontal diaphragms are to be introduced at the top and bottom of the silos. The deep transfer beam built adjacent to the silos and the new diaphragms at cut level and top level will span between super columns, which are the silos that are not cut at 5th floor (+22.1). These columns are partially demolished, so in order to prevent them from buckling due to their reduced thickness (150mm), as well as to guarantee that they can take the additional loads, they will be strengthened with an additional outer concrete layer attached to the existing one and increasing its overall thickness.

Two beams must be executed at the same slab level in order to support the cut silos which do not reach foundation level and therefore have no support. The solution of adding a new silo-column to foundation allows that the row nearest to the expansion joint can work as a cantilever, avoiding that the new beams must be supported at the edge of the 1935 silos.

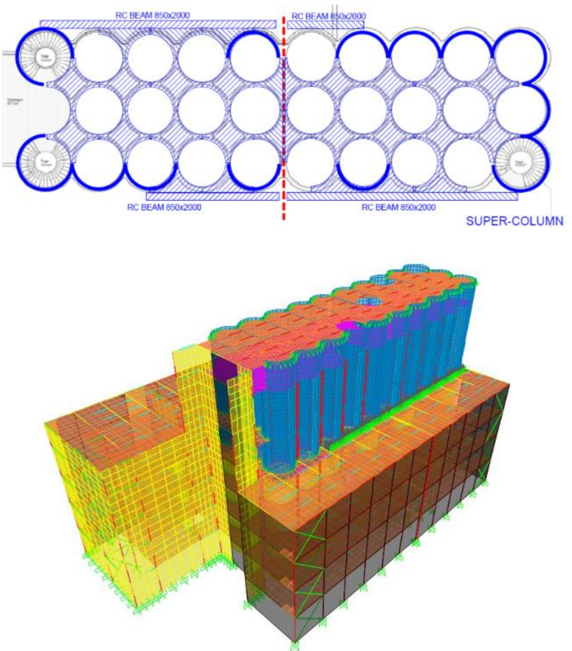

Figure 10. Plan of the diaphragm slab and F.E.M. view.

3.2 Adjacent Buildings – Two standard buildings connected to their respective silo

In this case, the structure is more conventional, and will be governed by the long spans, as well as the necessity to provide a lateral bracing stability system to mitigate the impact of the wind loads on the silos structure. In order to provide the required spans without columns at the exhibition areas, a system of composite metal deck spanning between long span cellular beams has been designed. The holes of the cellular beams will allow for passing the conducts for services.

3.3 Foundation – A common foundation for all buildings

The foundations of the East and North buildings consist of a basement slab at the underground level and isolated footings for the areas outside the basement. Both foundations bear at the same level, directly onto rock or onto filling layers where the rock bed is lower. The basement slab is tied down with ground anchors to withstand the ground water pressure. In relation to the silo foundations, the existing foundations from 1935 are strip footings bearing directly to rock and will now be enlarged and strengthened. The 1939 foundations consist of columns that are not found reliable and are disregarded in the project. As a result, the foundation is executed by means of steel core piles and inclined/vertical steel bored piles. The foundation of the new West building is also steel bored piles.

4. Construction sequence

One of the key factors for the success of the project is to develop a construction sequence that establishes the correct order to execute the demolition and reinforcement works without compromising the stability of the remaining silos. The final sequence has been carefully planned and discussed with the future Contractor (Kruse Smith) to guarantee the viability of the different phases.

A detailed analysis has been performed of the structure during the different construction phases: A FEM Model simulating the different erection and demolition stages has been implemented and the structure has been verified at the end of the different construction stages, as well as for the final building configuration. The following are the main phases of the construction:

4.1 Phase 1: Demolition of the auxiliary buildings around the silos.

This phase includes the demolition of the light steel structures on top of the silos, the demolition of the six storey annex building, made of reinforced concrete, located to the west of the silos and the demolition of the stair communication core located to the north. The idea is to leave standing only the old silo constructions, which are self-supporting structures.

4.2 Phase 2: Preparation works and rehabilitation of the existing silos.

It is necessary to open up some holes in the concrete slab at the top of the silos in order to allow the placement of auxiliary steel platforms that will be suspended inside the silo cylinders by means of steel cables. These platforms can be moved up and down to inspect and rehabilitate the interior of the silo walls. The rehabilitation of the existing silos consists of a combination of mechanical repair of the damaged concrete and the electrochemical re-alkalization of the interior part of the silos to halt the corrosion of the steel in the carbonated concrete. The mechanical repair will be done both inside and outside of the walls and it will include the removal of loose concrete, filling of damaged areas with mortar and the repair of all the cracks larger than 0.8mm width.

4.3 Phase 3: Reinforcement of existing foundations and execution of new foundations.

This phase includes the reinforcement of the existing direct foundations to rock of the 1935 silo walls by means of their enlargement with new pad foundation, tied to the existing ones. This way the additional loads at the remaining silo walls will be transferred safely to the sound rock below. The 1939 silos have deeper foundations with variable length RC concrete columns to the rock. New small diameter steel core piles can be installed inside the silo walls with small machinery and large diameter steel tube piles can be installed outside the remaining silo walls (super-columns) to transfer the additional loads. Large pile caps will be cast connecting the interior piles to the remaining silo walls and the large diameter exterior steel piles. A new ground floor concrete slab will be cast to connect and tie all the interior elements inside the silos.

4.4 Phase 4: Reinforcement of the existing silo construction.

All remaining silos below +22,10 m (cut level), which support the silos above the cutting level (super-columns), shall be reinforced from outside with a minimum of 200mm concrete with a double reinforcement layer.

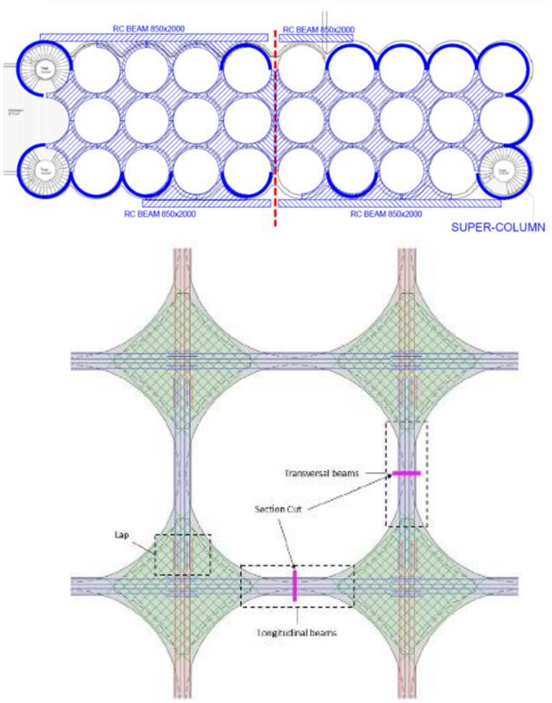

Figure 11. Plan of the diaphragm slab at cut level.

A diaphragm of reinforced concrete 450mm deep will be executed directly above the cutting level (+22.50m) to tie the base of the silos and to support them. This diaphragm has also circular openings aligned with the interior silo walls to respect the architects design, but an orthogonal grid of beams 350mm wide will be executed to transfer the forces in two directions. Local cuts will be done at the existing walls to cast the new diaphragm. There are two powerful lateral RC beams to distribute the loads to the remaining super-columns below. Exterior silos over 22,10m (cut level) shall be also reinforced to withstand the tension forces.

4.5 Phase 5: Demolition of existing silo walls below the cut level.

When all the reinforcement works have been executed, it will be safe to proceed carefully to the cut and demolish the silo walls.

Only new reinforced external walls will be maintained. Demolitions will start from the cut level progressing downwards to the ground level. Subphases for the demolitions have been carefully planned, with a maximum of six cylinders affected per stage. The works will start at the south, starting with exterior walls to permit the access to the interior rhomboidal walls. In total 17 demolition subphases have been planned.

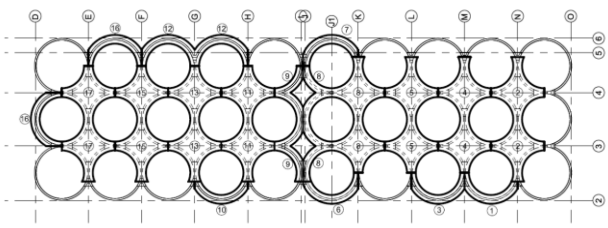

Figure 12. Demolition sequence below the cut level.

4.6 Phase 6: Execution of new buildings around the remaining silos.

After finishing the demolition of the concrete silo walls, the works to erect the new annex buildings at west and east of the silos can start.

The structural system of the new buildings consists of steel columns placed at the façade alignments that support large span steel cellular beams and composite slabs. Where necessary cross bracing elements have been designed to guarantee the horizontal stability.

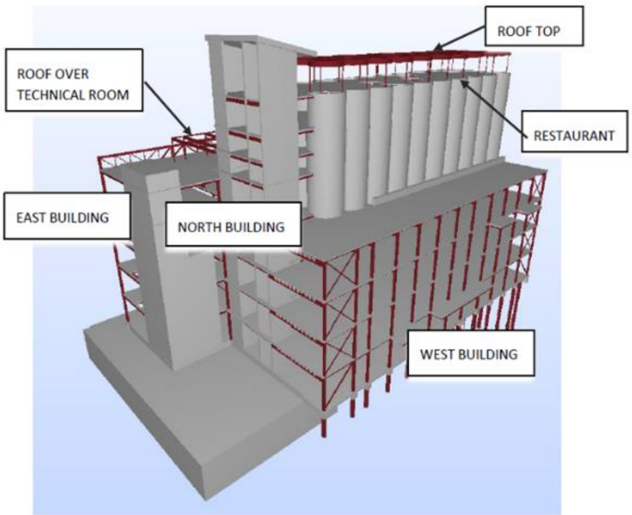

Figure 13. Buildings around the silos construction.