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USE OF BASE ISOLATION WITH DAMPING IN AN INDUSTRIAL STRUCTURE RETROFIT

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Abstract: *This presentation involves a project recently executed in a cement production plant in Greece, within the framework of a general plant upgrading, to replace coal burning by waste incineration. An existing reinforced concrete preheating tower approximately 53m in height required to be retrofitted, resulting in an additional 880 tons of equipment. The existing tower had been built in the 1970's with a uniform design acceleration of 0.06g, while the Owner required the intervention to also upgrade the structure to current seismic design standards (EN1998 with 0.24g peak ground acceleration). Several options were investigated and a solution involving base isolation with damping was finally selected. This allowed the upgrading of the structure to current seismic accelerations with relatively simple reinforcing measures. The challenges faced included issues related to the high magnitude of loads to be carried, the congestion of equipment and the uncertainties associated with interventions on existing structures. The full implementation of 3D technology in all phases of a construction project (from initial surveying of the existing structures to the BIM modelling of the design and the coordination with all involved disciplines) proved to be particularly helpful.*

Project background and design constraints

The production plant of TITAN Cement Company plant near Athens, Greece is being converted to replace coal burning by burning of Refuse Derived Fuel (RDF). RDF is an efficient alternative fuel form, derived from special waste, such as non-recyclable plastics, papers, etc and it is partly carbon neutral. The switching of a cement plant from coal burning to RDF burning introduces significant alterations along the production sequence. These include the installation of a pre-calciner upstream of the preheater, a tertiary air duct in parallel with the kiln, as well as modifications and/or replacement of existing cyclones, a new RDF storage facility and a new RDF feeding conveyor. The pre-calciner is to be partly supported by a new structure and partly supported by the existing preheater tower. The arrangement of the existing production line is shown in Fig.1 and the intended interventions are indicated schematically in Fig. 2. The design work was carried out during the period 2017-2019 and the construction was carried out during the period 2020-2022.

The plant regularly operates two parallel production lines on a 24-hour basis. The RDF burning conversion involves the 1st production line. The 2nd production line is to remain operationally unhindered by the conversion process, including construction activities. Furthermore, the 1st line is only allowed to be stopped for limited durations, to allow for the implementation of the conversion to RDF burning.

It is evident from that photograph that one of the main considerations in the design was the limited available space, which was further aggravated by the need to maintain the roadways unobstructed. The design needed to separate construction and erection stages into several phases:

1. Enabling works Phase 1: Works that can be carried out with both production lines operating at full capacity.
2. 1st stoppage of Line 1: Brief interruption in the operation of Line 1, to allow the implementation of essential works related to the conversion to RDF burning.
3. Enabling works Phase 2: Works that can be carried out with both production lines operating at full capacity.
4. 2nd stoppage of Line 1: Completion of all works that require production stoppage.
5. Completion works: Line 1 restarts having been converted to RDF burning. The works carried out in this phase correspond to secondary finishing works.

The plant was built in the 1970s, according to the valid earthquake code at that time, which prescribed a uniform design acceleration of 0.06g. The Project specifications required that any structure undergoing modifications in its structural system or receiving increased loading, because of the retrofit, be reinforced to comply with current seismic legislation. The currently valid earthquake design code in Greece is EN1998 and the Greek National Annex specifies a peak ground acceleration of 0.24g for the Project region. This placed a formidable constraint on the design, since structures designed to a 0.06g uniform horizontal acceleration cannot be easily upgraded to design accelerations resulting from a 0.24g peak ground acceleration per EN1998, without a significant overhaul of the entire structural system.

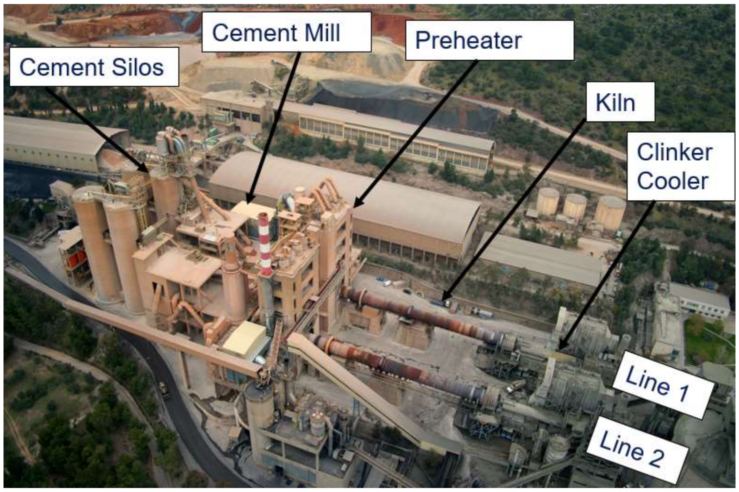

Figure 1. Aerial view of the 2 production lines of the plant (photo from AMTE archives).

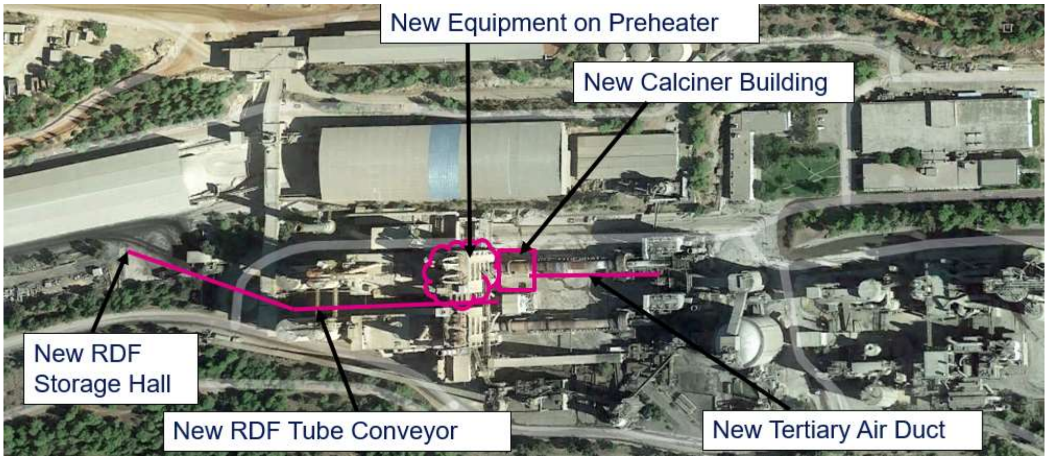

Figure 2. View of the plant with marked major interventions (photo from Google Earth).

Design procedure

The complexity of the work and the space constraints dictated careful preparation and a tight coordination procedure. Building Information Modelling (BIM) was adopted for all stages of the work. Despite the existence of detailed as-built drawings, the project area was surveyed by the Owner through laser scanning, resulting into a 3D model of the existing structures and equipment (Fig. 3). This model was the basis for the designs carried out by the different disciplines. The Project coordination model included the as-built scanned model and all models created by the different disciplines (Fig. 4 depicts the scanned existing situation and the planned new equipment). The coordination among all disciplines was carried out by the Technical Department of TITAN Cement Company.

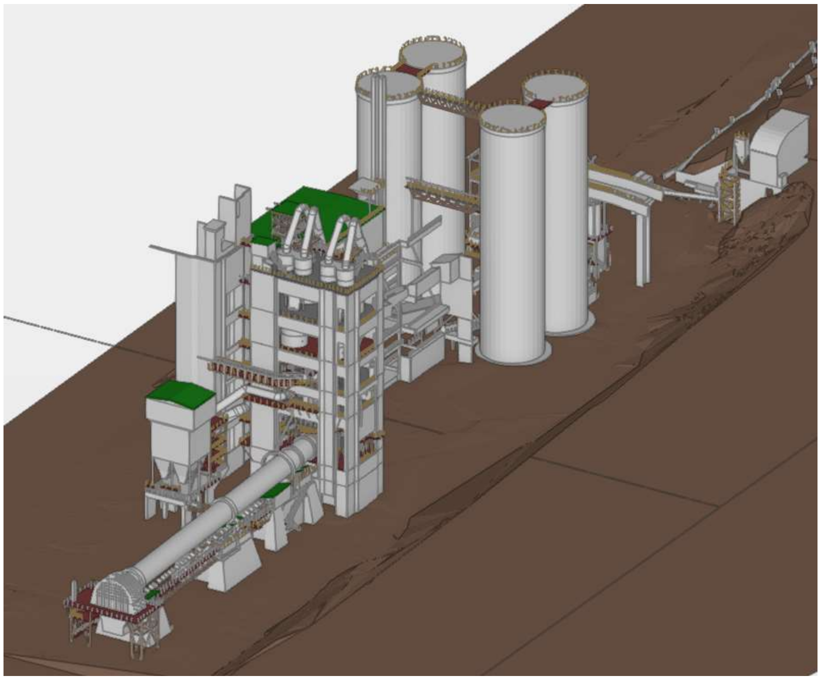

Figure 3. BIM model of scanned existing structures & equipment.

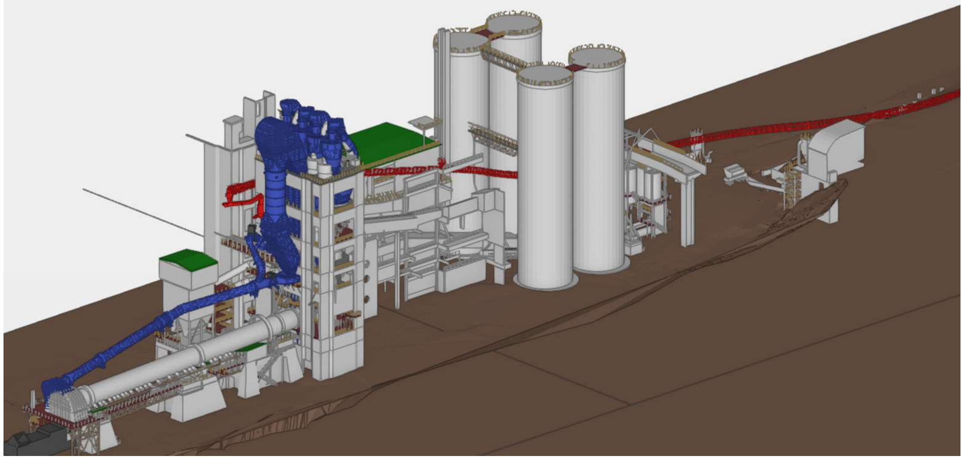

Figure 4. BIM model of scanned existing situation with planned new equipment (in blue & red).

Description of structure

The preheater building (Fig. 5) is a reinforced concrete structure with plan dimensions 25.90m × 15.70m and height of 53 m above ground. There are 6 main intermediate levels with concrete slabs, several smaller steel platforms, and a roof level reinforced concrete slab. The existing equipment corresponds to about 1185 tons, while the conversion to RDF burning would increase the total equipment weight in the building to about 1960 tons, which represents an in crease of 65% in equipment dead loads of the structure.

Fig. 6 (left) depicts the new equipment planned for the region of the existing preheater building. A new structure was planned in front of the preheater building to house the equipment outside the existing building (Fig. 6, right). The need for this new structure further complicated the design procedure, as the available space around the preheater building would thus be significantly reduced. Therefore, the construction sequence needed to allow for the simultaneous erection of the new structure and its equipment, while at the same time enabling access to the preheater building intermediate and roof levels for erection activities there as well.

Figure 5. Preheater buildings for Lines 1 & 2 (Line 1 on the right).

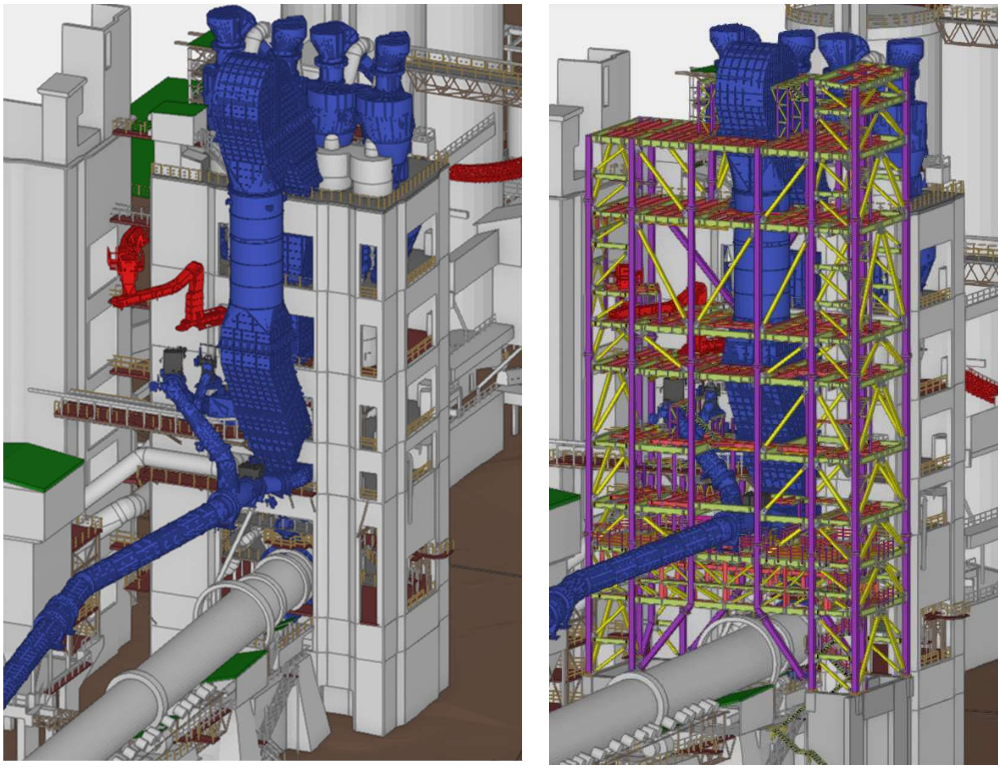

Figure 6. Preheater building with planned new equipment (left) & new structure planned for the support of equipment outside the preheater building (right).

Earthquake considerations

The existing preheater building had been designed for a uniform horizontal acceleration of 0.06g, according to the requirements of the 1959 Greek seismic code. Since significant additional loads are being applied, the Project specifications required that the structure be upgraded to the seismic acceleration levels of the current code. For a 0.24g peak ground acceleration, soil type A and importance factor 1.0, the elastic maximum design acceleration according to EN 1998-1 is 0.60g. The main load resisting system of the structure consists of reinforced concrete shear walls. Consequently, elastoplastic energy consumption through controlled damage in the shear walls is not expected to be significant. Therefore, a low behaviour factor has been assigned (q=1.5).

On the basis of the above, the initial calculations resulted in extensive requirements for reinforcement of the existing structure. Some of the areas to be reinforced were difficult and even impossible to access: At the whole back façade of the structure, existing equipment on the ground and ducting and cabling on the walls do not allow safe access (through scaffolding or crane) for reinforcement works, thus requiring prohibitive dismantling works. The results indicated also that the existing foundation needed reinforcement.

Alternative solutions were therefore sought. The initial approach was to connect the preheater building to the new structure, thus using the new structure for additional seismic reinforcement of the preheater. Design initially proceeded along this way and the new structure was being planned as a reinforced concrete structure, in order for it to possess the necessary stiffness to enable the lateral load sharing between preheater and new structure. During the course of the design however, successive increases in the equipment loads of the new structure and operational constraints in the size of its shear walls gradually reduced the effectiveness of the new structure in overtaking a significant share of the combined seismic shear. Hence, a different approach had to be found.

The realization that a significant part of the additional equipment loads (about 500 tons) were to be installed above the roof level of the preheater led to the decision to base-isolate that level. The roof level concrete slab would be demolished and the whole new roof superstructure with its corresponding equipment would be separated from the existing structure through a base-isolation system consisting of elastomeric bearing pads and dampers.

Design of base isolation

The existing concrete roof slab is cut off and replaced by a stiff perimetric steel beam supported on the existing perimetric walls by elastomeric bearings. The new superstructure and the new equipment at or above roof level would therefore be supported on this beam and be seismically separated from the existing structure. Additionally, friction dampers are used to dampen the seismic energy of the base-isolated superstructure, so that the final seismic impact on the existing structure is significantly reduced. The arrangement is shown in Fig. 7 & 8.

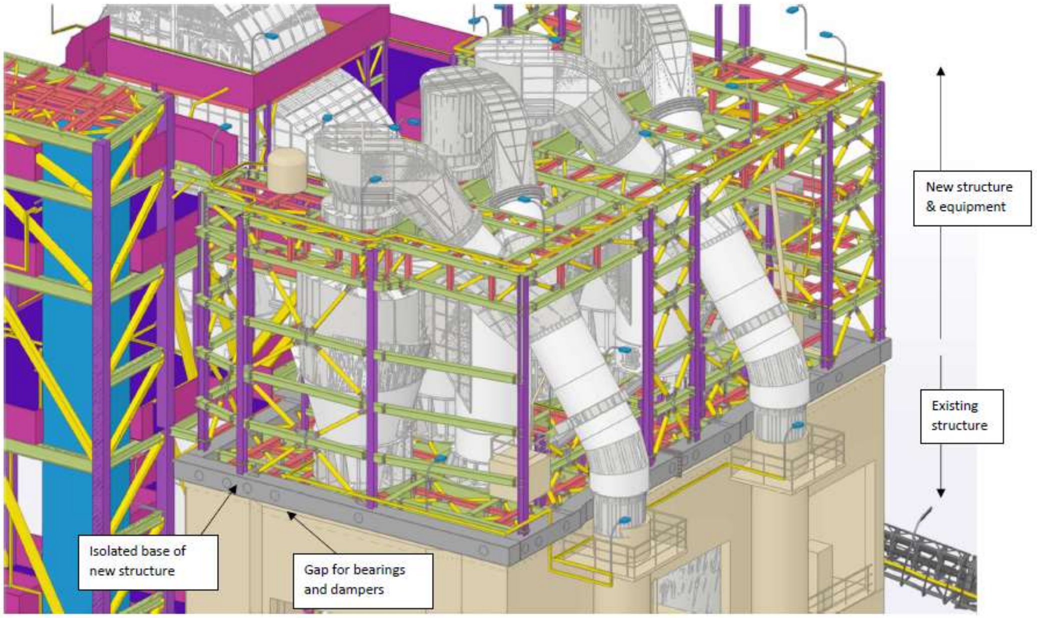

Figure 7. Overview of base-isolated superstructure.

The bearings are placed along the perimeter of the outer walls in such a way as to avoid uplift under the lateral load combinations. A total of 19 bearings are placed. The dampers selected are bidirectional rotational frictional dampers supplied by Damptech (Damptech, 2023). They offer the advantage of bidirectional in-plane response, much like the bearings, thus simplifying the arrangement, particularly since the available space was constrained, as the support region coincided with the narrow outline of the vertical walls. A total of 15 dampers are placed, each damper having a nominal capacity of 100 kN and a stroke of 50 mm. The nominal capacity corresponds to the force level at which the damper is activated. This and the damper efficiency have been determined through a series of non-linear dynamic analyses described hereunder.

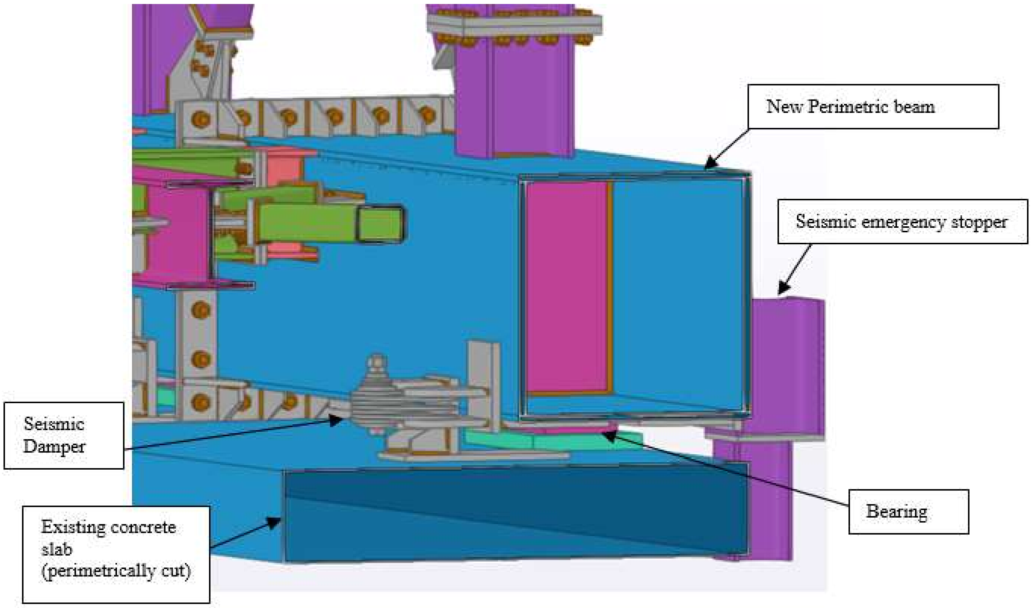

Figure 8. Base isolation concept – Vertical section.

A total of 6 real earthquake acceleration records were selected (Table 1). The selection criteria were as follows: Two Greek earthquakes were selected as representative of the ground motions usually recorded in Greece (in terms of magnitude, duration, peak ground accelerations and spectral peaks). The Kocaeli, Turkey motion record is representative of a large magnitude earthquake with relatively low peak ground acceleration and spectral peak. The Tabas, Iran earthquake was selected as being representative of a large earthquake with comparatively moderate peak ground acceleration, but long duration and significant spectral peak. The two USA records used correspond to usually selected reference ground motions representing moderate magnitude earthquakes with high spectral peaks. Since the motion records used correspond to actual earthquakes, they have not been scaled.

The dampers were modeled using non-linear elements corresponding to the Bouc-Wen theory of hysteretic behaviour (Bouc, 1971 and Wen, 1976), which is in line with the specific type of dampers. The preliminary analyses of the structure indicated that limited local reinforcement of the short side shear walls could upgrade the structure to a 0.20g design acceleration. It was therefore aimed at providing sufficient energy dissipation to limit the seismic shear to that level. Hence, for an 880-ton mass at the top of the preheater building, a 1500 kN damper nominal capacity was assigned (15 dampers × 100 kN), corresponding to a base shear ratio of 1500/8800 = 0.17 g. It is pointed out that the non-linear dynamic analyses were carried out on a simplified model using a single representative link element lumping the damper properties and a single mass corresponding to the superstructure. Hence, the structural damping provided by the bolted steel superstructure is conservatively not accounted for in the total damping calculated. The analyses were carried out by ETABS (ETABS, 2023).

Location	Year	Magnitude	Peak Ground Acceleration	Spectral peak	Achieved Damping
Kalamata, Greece	1986	6.0 R	0.24 g	0.85 g	76%
Thessaloniki, Greece	1978	6.5 R	0.14 g	0.47 g	81%
Kocaeli, Turkey	1999	7.6 R	0.16 g	0.71 g	89%
Tabas, Iran	1978	7.4 R	0.33 g	1.40 g	92%
Loma Prieta, USA	1989	6.9 R	0.46 g	2.00 g	98%
Northridge, USA	1994	6.7 R	0.27 g	0.81 g	84%

Table 1. Acceleration records selected and achieved damping.

The results shown in Table 1 indicate that the dampers effectively consume sufficient energy to reduce the base shear to below 0.20g, so that the structure can be safely upgraded to the current code seismic acceleration levels. Fig. 9 summarizes the results corresponding to the non-linear dynamic analysis for the Kocaeli, Turkey acceleration record. The input seismic energy is represented by the total area below the green line in the graph on the left, while the damper hysteretic energy is represented by the total area below the yellow line in the same graph. The graph to the right of Fig. 9 depicts the load displacement curve for the lumped damper element. The dampers are activated at their nominal capacities (100 kN × 15 dampers = 1500 kN) and their maximum deformation is 28 mm. This curve also highlights the advantage of the frictional dampers with respect to liquid dampers for the specific application. Frictional dampers are force-based, hence result in linear hysteresis loops, as the force remains constant after slip, while liquid dampers result in elliptical hysteresis loops, as they are based on velocity which varies during their activation. The total energy consumed by the dampers being the total area enclosed by the hysteresis loops is maximized in rectilinear hysteresis loops compared to elliptical ones.

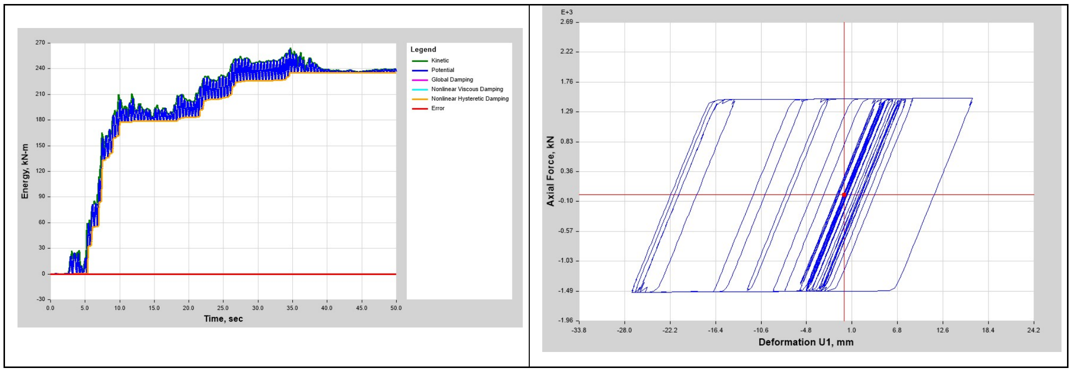

Figure 9. Kocaeli record: Energy graph (left) & Damper load displacement curve (right).

Detailed design

The detailed design included the steel superstructure, the reinforcements for the existing structure, the detailing of the base isolation system and the design for the erection. The analysis and design of the steel superstructure and the reinforcements for the existing structure were carried out by finite element analysis software DLUBAL (DLUBAL, 2023).

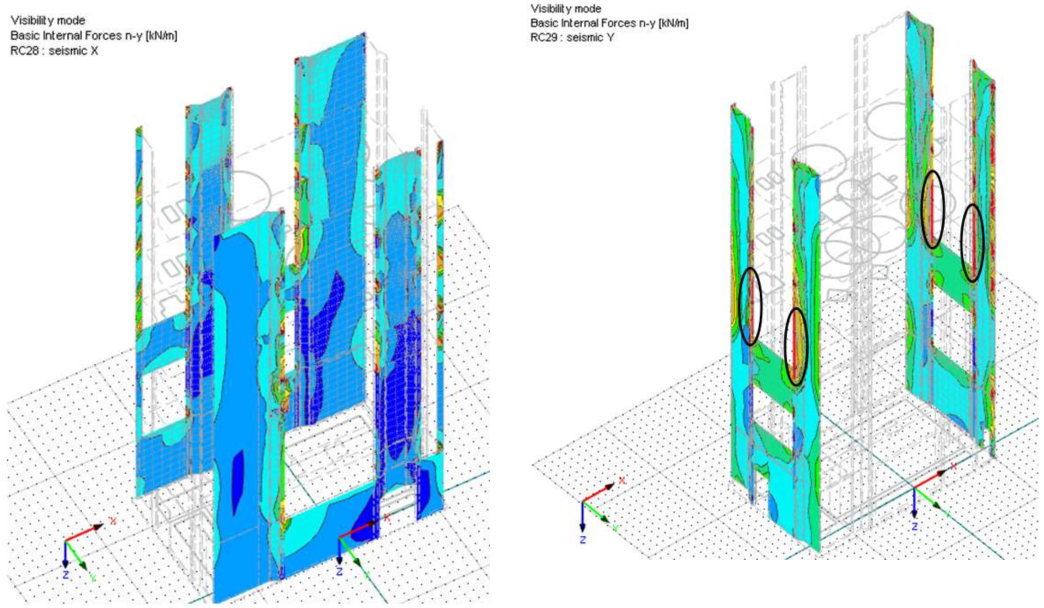

Figure 10. Seismic vertical forces on shear walls. Regions requiring reinforcing highlighted (right).

The shear wall reinforcements were introduced in the form of reinforcement bars embedded in sprayed concrete jackets dowelled to the shear walls.

The detailing was carried out through BIM modelling in Tekla Structures (Tekla, 2023). The perimetric beam detailing included the connections to the bearings and the dampers, the stoppers for the case of excessive seismic deflection demand and the uplift restrains (Fig. 11 & 12).

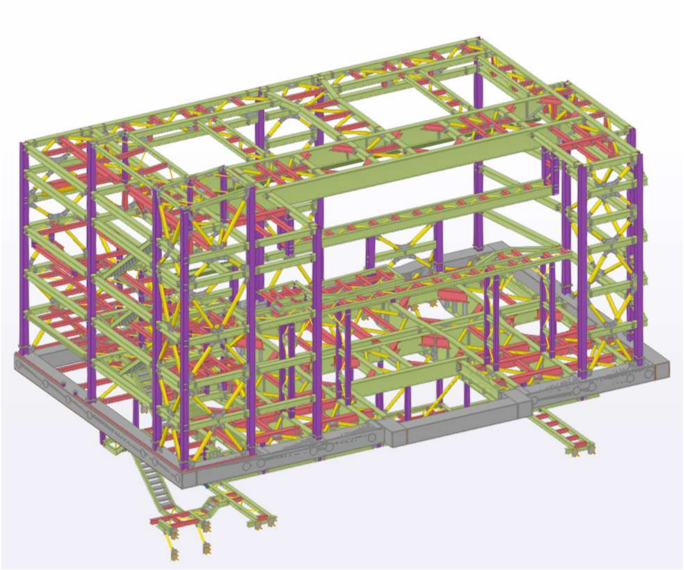

Figure 11. Fabrication model of the steel superstructure.

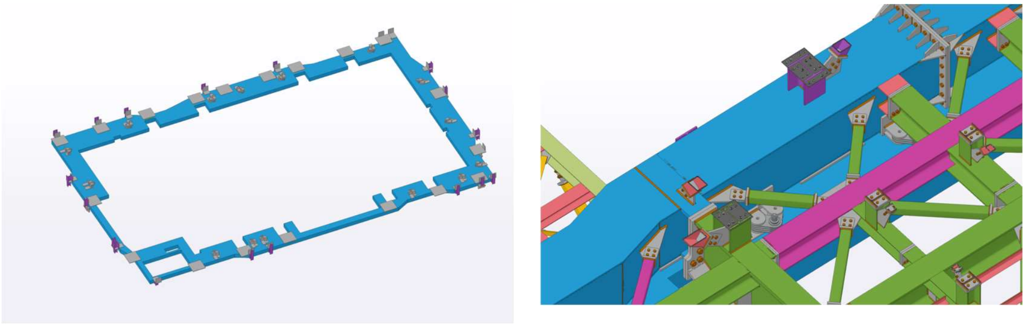

Figure 12. Fabrication model details: Bearings, dampers, stoppers (left), Perimetric beam connections (right).

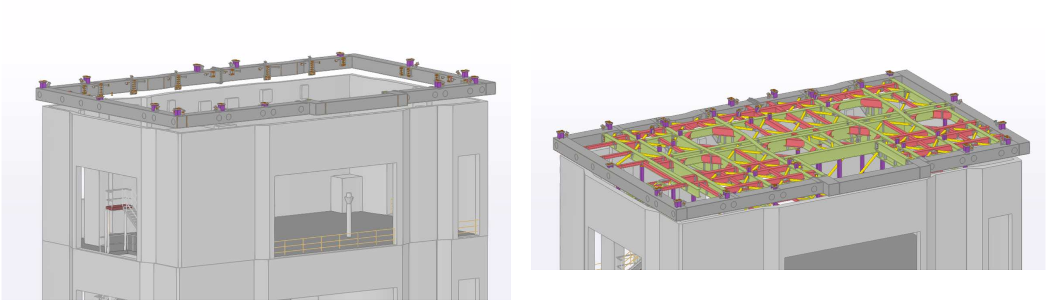

Figure 13. Erection: Perimetric beam (left), Superstructure up to perimetric beam (right).

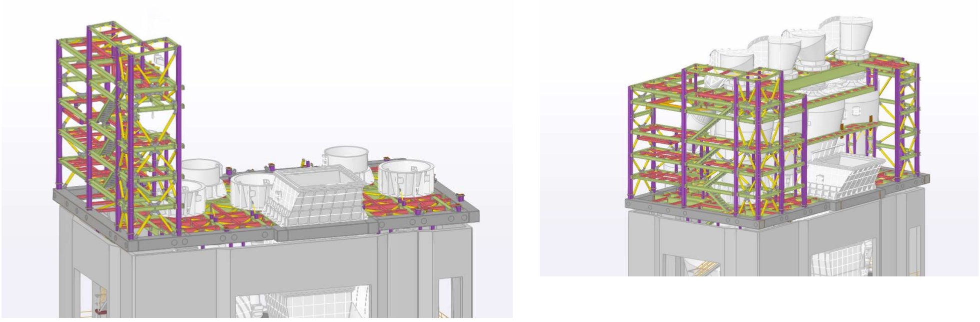

Figure 14. Erection of large lift units equipment (left), completion of erection (right).

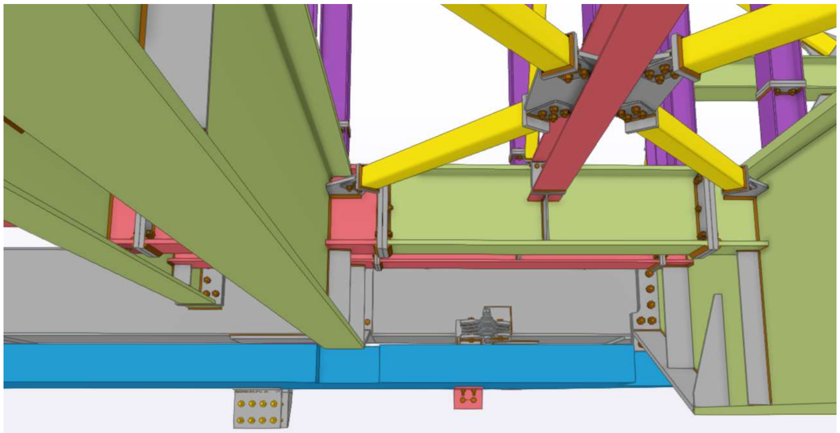

Figure 15. Detailed view near perimetric beam (corresponds to the photograph in Fig. 15).

Construction

The following images (Fig. 16 & 17) correspond to photographs taken after the completion of the erection of the superstructure and its equipment.

Figure 16. Overview of preheater building (left) and completed superstructure (right).

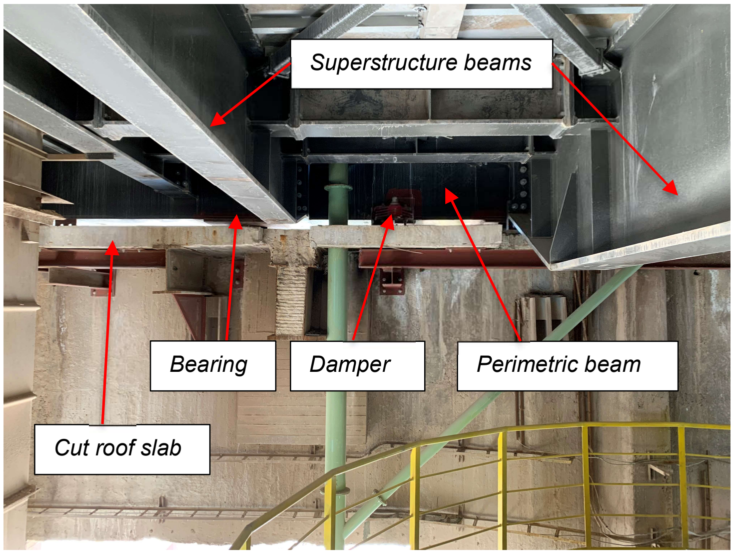

Figure 17. Inside view of characteristic base isolation elements.

Conclusions

The use of base isolation with damping allowed the successful implementation of a large mass addition to an existing structure with parallel upgrading to a significantly higher design earthquake. The use of dampers constitutes a fully controlled seismic energy consumption: The energy is consumed by a product industrially manufactured for that purpose, as opposed to relatively arbitrary assumptions concerning the percentage of seismic energy reduction attributable to a vaguely defined level of structural damage.

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