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RESEARCH ARTICLE

Damage assessment of a cement plant partially collapsed depending on various causes

Uğur Emre Temelli[1], Cüneyt Öngören[2], Baris Sayin[3]

[1] Istanbul University-Cerrahpaşa, Vocational School of Technical Sciences, Istanbul, Türkiye
[2] Project Engineering Company, Istanbul, Türkiye
[3] Istanbul University-Cerrahpaşa, Department of Civil Engineering, Istanbul, Türkiye

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Abstract

This study aims at examining the possible causes of the brittle collapse of a tertiary air duct system under vertical loads. Problems related to the design and construction stages were examined. The entire process was illustrated using a tertiary air duct case study in a cement plant. In the plant, the tertiary air duct collapsed without any earthquake, blast, or impact effects. The current study includes a field study, examination of an original/revised design project, and numerical simulation. In the first stage of the study, the existing state of the collapsed system and its compliance with static and mechanical projects were examined. Secondly, a two-dimensional finite element analysis was performed to determine project eligibility. The causes of the system were determined based on the data obtained in the former stages. The results showed that the causes of partial collapse included project errors, construction faults, and project incompatibilities.

1. Introduction

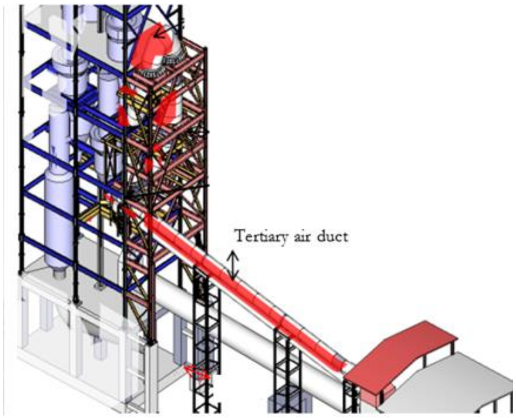
In structural systems, the design stage is mostly carried out considering vertical and lateral loads. Plus, heat, wind, and snow loads are also considered depending on the properties of the systems. The ultimate goal in the design of a structure is to prevent a collapse. Other goals are related to the effective use of the structure. Therefore, the main purposes of the design are to ensure the life safety and functionality of the structure. A structural collapse is mostly associated with the errors made in the design and/or construction stages. Furthermore, a collapse may occur as a result of exposure to impact or blast loads unforeseen at the design stage. However, such a scenario is mainly an exceptional case.

In the design stage of structural systems, static, mechanical, and architectural projects are prepared and the construction stage is then carried out based on these projects. However, structures built using faulty projects can eventually collapse under various load conditions. In addition, although projects are accurate and error-free, there may be a lack of audit practices during construction. In this case, the construction would probably not comply with the project requirements which may eventually lead to a collapse. A collapse may also occur due to project revisions. If a project is revised, the revised project should comply with all other related projects. Otherwise, this may lead to partial or whole structure failure.

A cement plant construction can be considered a large-scale engineering project and therefore, it should be carefully planned before starting the construction. Fig.1 provides views of a cement production plant [1,2].

Correspondence Baris Sayin barsayin@iuc.edu.tr

a)



b)

Fig. 1. (a) A sample cement production plant [3], (b) Schematic view of a cement kiln [3]

A cement plant construction consists mainly of three stages: i. Finding the most appropriate location for the cement plant, ii. Designing, iii. Carrying out the plant construction & installation of equipment. Before starting the construction and installation stage, the design of the cement plant is completed.

A literature survey revealed that only a few studies have examined structural damages in cement plants. Various factors can cause collapse or damage in cement plants [4]. For example, a previous study investigated the earthquake and tsunami-induced slab damages in a cement factory. Repair and strengthening practices considering crack formation and the current strength of the structure were presented [5]. In that study, static and dynamic analyses for the structure were carried out based on the current building regulations. As a result of the analyses, the existing bending capacity of the structure was determined to be insufficient. Furthermore, mechanical fatigue damages in a cement plant were examined by another study [6]. Damages that occurred due to material content were also discussed [7]. Damage caused by vertical loads on the flat slab was also examined [8]. In that study, the causes of the collapse of the slab system without any earthquake, blast, or impact effects were examined. The authors determined that the collapse occurred due to a design error.

Mostly, blast or dynamic loads lead to the collapse of the structure or structural elements [9]. On the other hand, in some cases, collapse can occur in structures only under the effect of vertical load without these effects. However, structural collapse occurs as a result of the collapse of the columns due to design errors or construction faults [10]. To the best of our knowledge, no study has yet examined a design error and/or construction fault-induced collapse in an existing cement plant. Therefore, the current study examines the possible causes of a partial collapse that occurred in a cement plant without exposure to any seismic or impact effects based on field survey and numerical analyses. During the field survey, damage status was investigated with visual examinations. In the numerical studies, a 2D finite element model of the tertiary air duct was prepared and numerical analyses were performed considering the seismic code in the construction year of the tertiary air duct. Accordingly, the reasons for the collapse of the tertiary air duct were identified.

2. Examined cement plant

The examined plant was established in the 1950s. Later on, since the clinker line had completed its service life, it was replaced by a rotary furnace with a dry system. After the improvements were made to the rotary furnace unit, the furnace capacity was increased [11]. In 2018, the production capacity was increased with the modernization of the cooling tower and tertiary air duct (Fig. 2). Just two months after this modernization, the tertiary air duct collapsed.

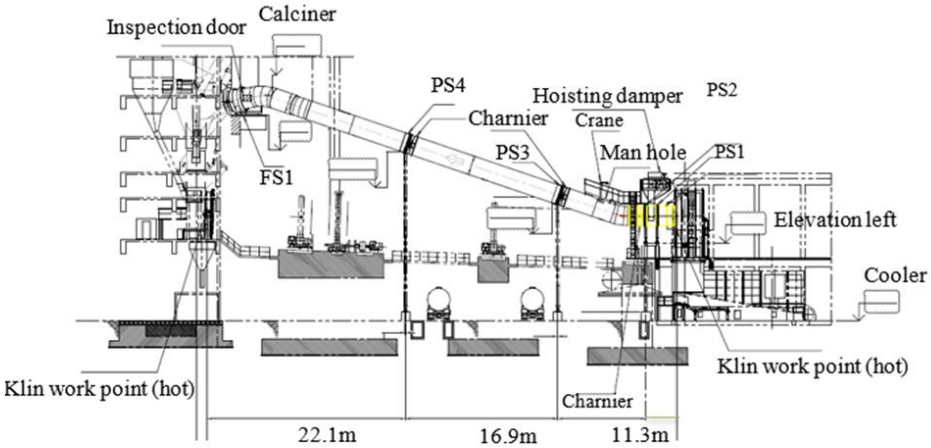


Fig. 2. Elevation view of the cement plant

2.1. Project review

A static project [12] was prepared for the modernization of the tertiary air duct system. This system consists of a duct and columns. The columns were constructed according to this project. However, it was later understood that there was not sufficient space between the duct columns for a vehicle passage. Therefore, the static project was revised. In this revision [13], the PS3 and PS4 columns were shifted by 5.8 m and 2.8 m, respectively as shown in Fig. 3. The space between the PS2 and PS3 columns, which was 9.6 m before the revision, increased to 15.4 m (=9.6+5.8). Furthermore, due to the column movements, the heights of the PS3 and PS4 columns were increased by 1.9 m and 0.9 m, respectively as in Fig. 3. For this purpose, some additions were made to the columns as shown in Fig. 4. Consequently, the pin positions of the duct were also shifted by 2.8 m and 6.1 m along the duct axis. Also, the footing thickness of the PS4 column was increased.

2.2. Field survey

During the field survey, inspections were conducted in the collapse area. The interventions performed according to the revised static project and mechanical project were visually examined to determine whether the projects were carried out accurately. Data about the possible causes of the collapse were also obtained during the field survey. Fig. 5 provides the post-collapse images of the duct (indicated by *A* in Fig. 3). The duct and column movements during the collapse are schematically shown in Fig. 6.

3. Numerical modeling

The structural performance of the duct system was determined according to the assumptions and the parameters given in TEC 2007 code [14]. SAP2000 [15] and Limcon [16] software were used in the modeling and analysis of the system. A linear elastic analysis was performed for the structure under earthquake loads to determine if the design is faulty. Fig. 7 displays the model of the system used in the analysis. However, no information was obtained about the loads considered in the revised static project. Therefore, for column end loads, the values specified in the original mechanical project were used. The parameters for the numerical analyses are given in Table 1.

Since 8.8/10.9 quality bolts and S235/S275 structural steel were preferred in the design project, the same materials were selected in the model. Dead loads were determined based on member weights. The load definitions are given in Table 2. The loads applied to four columns (PS 1 to 4) are given in Table 3. The load combinations for the analyses were determined based on the ASCE7-05 [17].

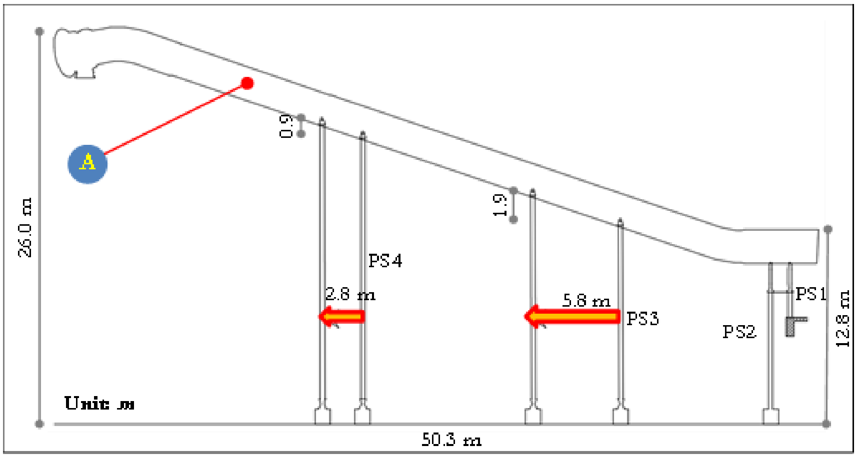


Fig. 3. Overview of tertiary air duct and the column movements

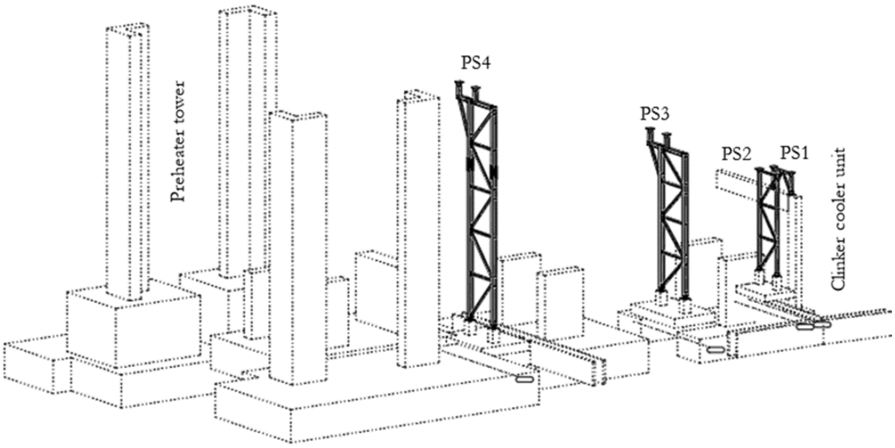


Fig. 4. An isometric view of the tertiary air duct (The duct indicated by A in Fig. 3) was placed on the columns PS1, PS2, PS3, and PS4)

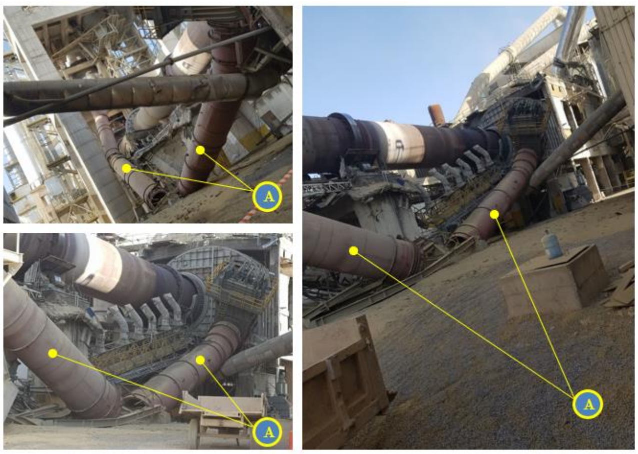


Fig. 5. View of the collapsed duct system

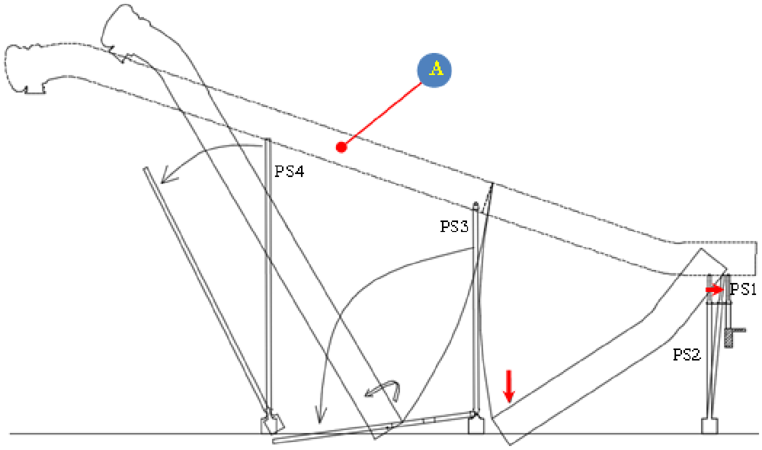
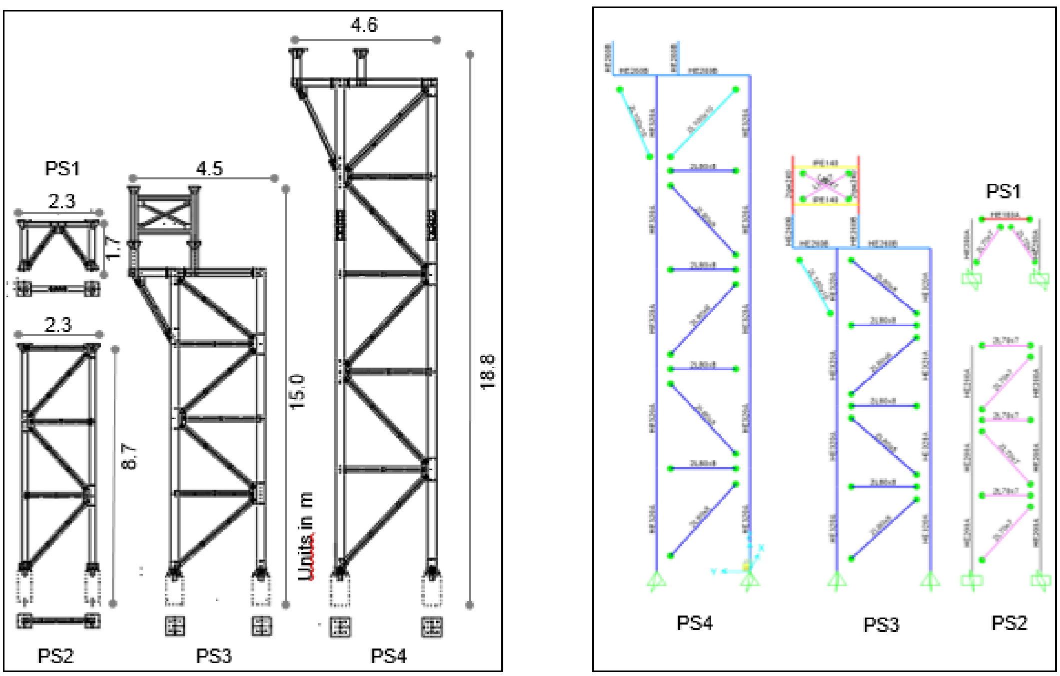


Fig. 6. The schematic view for the collapse of the duct system



a) b)

Fig. 7. (a) The planar truss system, (b) Structural models

Table 1. The soil and seismic parameters

Parameter	Class / Value
Earthquake zone	2
Effective ground acceleration coefficient, A_o	0.3
Building importance factor, I	1
Local soil class	Z2
Structural behavior factor, R	4
Material	S235JR – S275JR

Table 2. Load definitions

Load ID	Definition
DL1	Dead load of duct
DL2	Dead load of isolation
WL	Wind load
LL1	Snow load
LL2	Dust accumulation
EQ	Earthquake load
T	Heat load

Table 3. Loads applied to the columns [18]

Column ID	Load type	DL1	DL2	LL2	LL1	EL1	WL	EQ
PS 1	V	65	99	56	7	25	±0	±9
	H	1	1	1	0	0	±5	±45
	M	0	1	0	0	0	±17	±130
PS 2	V	119	141	129	12	25	±1	±38
	H	1	2	2	0	0	±8	±51
	M	1	1	1	0	0	±20	±135
PS3	V	114	267	172	31	0	±3	±39
	H	0	1	1	0	0	±35	±107
	M	8	17	10	2	0	±72	±220
PS4	V	148	374	165	43	0	±1	±26
	H	2	4	1	0	0	±35	±88
	M	12	29	13	3	0	±72	±182

V: Vertical (kN), H: Horizontal (kN), M: Moment (kNm)

4. Results and discussion

The results of the field survey and numeric analyses are presented in this section. These findings are discussed based on relevant standards and references [19-22].

4.1. Effect of construction faults on the collapse of the duct system

During the field survey, we detected that some construction practices were not consistent with the static and mechanical projects. The cold position of the column footings was mounted incorrectly. We found that the cause of this fault was due to the column movement; the mounting positions in the mechanical project were not changed according to the revision in the static project [23]. However, the mounting positions could not be determined in the post-collapse examination (Fig. 8). Also, the RC column dowel dimensions were not consistent with the static design project. Although anchorage length for vertical rebars was specified in the static project as 30 cm [9], the actual anchorage length was measured to be approximately 8 cm in the field study (Fig. 9).

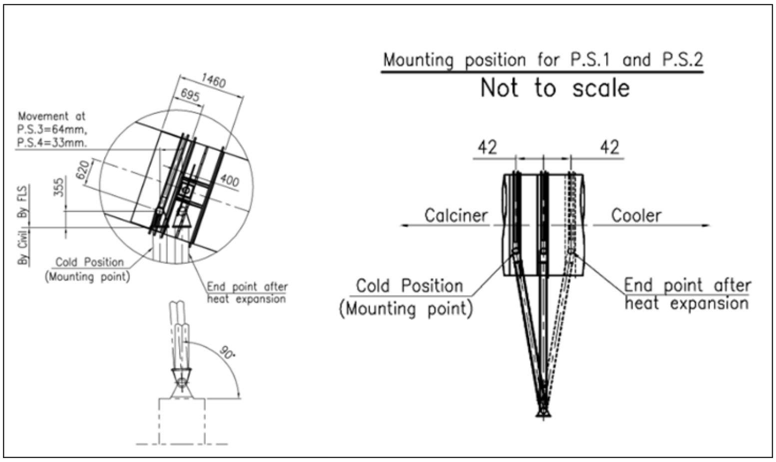


Fig. 8. Cold and hot-footing positions in the mechanical project (before and after expansion)

a) b)

Fig. 9. Anchorage lengths (a, b)

Although the thickness of the corner weld in the PS1 column footing-base plate joint should be 10 mm according to the static project, the actual welding thickness was measured to be 7 mm (Fig. 10). Furthermore, according to the design project, 12M16 anchor bolts should have been used in the PS3 and PS4 column footings. However, the field investigations revealed that 4M20 and 3M20 anchor bolts were used in PS4 and PS3 column footings, respectively (Fig. 11). According to the mechanical project, the lower and upper welds connecting the pin to the pipe should have been made by opening a welding mouth. The project states that there should be a 28 mm welding mouth on the 30 mm thick lower layer and a 12 mm welding mouth on the 15 mm thick upper plate. However, as seen in Fig. 12, the field investigation showed that the pin was welded without opening a welding mouth.

According to the mechanical project, the welds for the external ribbed plate should be 50–200 mm double-sided with a 10 mm corner welding. However, we observed that these welds did not comply with the dimensions specified in the project (Fig. 13). Moreover, in the mechanical project, welds for the duct attachment were defined as fully penetrated *V*-shaped welds by opening welding mouths to both plates. On the other hand, the field examinations showed that the actual welds did not comply with these requirements (Fig. 14).

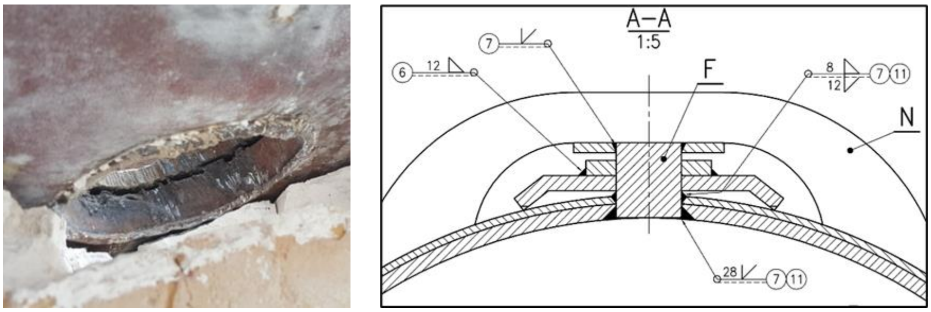
Although the mechanical project stated that there should be no missing bolts, some missing bolts were determined in the field inspections. (Fig. 15). Moreover, the project described that the lock plate, which was supported perpendicular to the pin cover, should be combined with 12 mm thick corner welds on both sides. However, these corner welds were not observed in the field study (Fig. 16).

a) b)

Fig. 10. Weld thickness measurements (a, b)

a) b) c)

Fig. 11. Anchorage measurements (a-c)

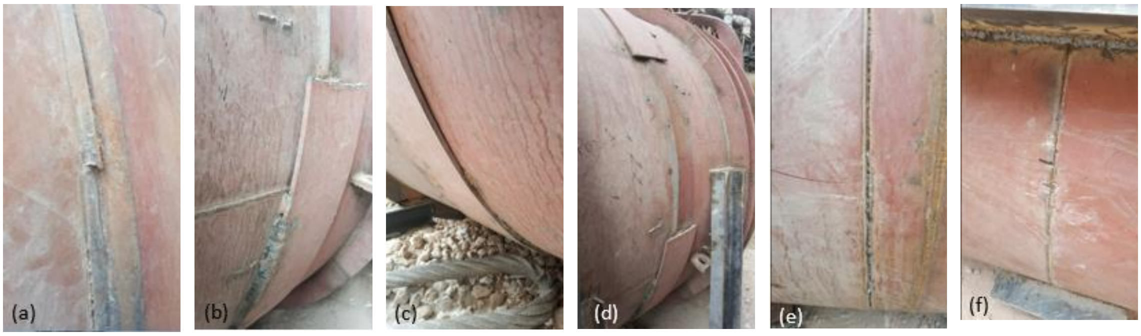


a) b)

Fig. 12. View of sub-welding in pin used for the duct attachment. (a) Actual image, (b) Project

a) b) c) d) e)

Fig. 13. External ribbing weld for the duct (a-e)

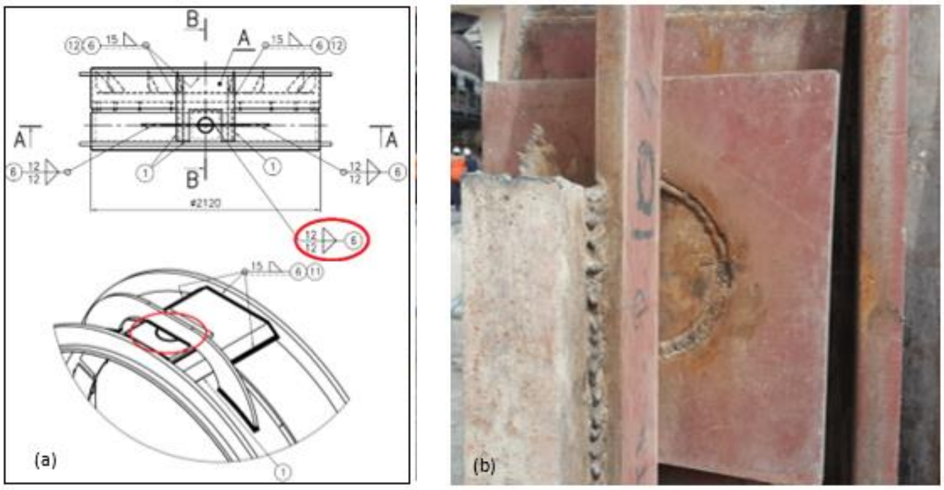


a) b) c) d) e) f)

Fig. 14. Additional weld for the duct (a-f)

a) b) c) d) e)

Fig. 15. Missing bolts detected in the hoisting damper (a-e)



a) b)

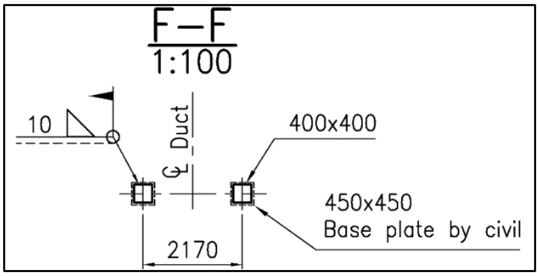
Fig. 16. Missing weld on the lock plate of the pinning zone (a, b)

4.2. Effect of incompatibilities between the projects on the collapse of the duct system

According to the revised static project, a 400×400×8mm plate should be placed over the PS3 column (Fig. 17a). However, this plate was described as 450×450×14 mm in the mechanical project. In addition, according to the mechanical project, the base plate of the upper joint should be connected to the plate over the column with a 10 mm corner weld. In the field study, we determined that the maximum deformations occurred on this plate (Fig. 17b).

We found that the pin on the duct system did not comply with the project requirements. However, a system collapse is still possible regardless of the accuracy of the pin application. Because the mechanical project was extensively revised. With this revision, the duct span increased to 16 m from 10 m, and thus, the duct section was exposed to increased moment forces by 2.6 times. This increase caused a change in the loads to which both the pins and the column ends were exposed. Therefore, the construction practice without properly revising the mechanical project is the main cause of the collapse.

Dimensions of the plate located at the end of the PS3 column in the revised static project did not comply with the mechanical project. In other words, plate dimensions and weld thicknesses did not comply with the project requirements. This defect can cause structural problems under earthquakes due to the great difference between the project and the actual practice in terms of the number of materials. However, it seems highly unlikely that the structure collapsed due to the compressive that the plate was subjected to under service loads. As shown in Fig. 18, it was observed that the column rotated towards to HE260B beam approximately 150 degrees during the collapse. Therefore, it is understood that the weld was still intact when the collapse started.



a)

b)

Fig. 17. (a) Column endplate (mechanical project), (b) View of column endplate after the collapse

Fig. 18. View of the column after the collapse

4.3. Effect of design errors on the collapse of the duct system

Fig. 19 provides design control results under the most unfavorable loading. Capacity ratios are also provided in this figure. The capacity limit was defined as "1". Accordingly, a number more than 1 indicates that the corresponding member has inadequate strength. The members with inadequate strength are indicated in red (Fig. 19). According to selected specifications and load combinations, 15-25% variation in element capacity values was considered within reasonable limits. If the structure had collapsed due to long-term use or earthquake damage, different load types should have been taken into account in the structural analysis. However, the duct system collapsed only two months after the modernization is completed, without any earthquakes, wind, and/or snow loads. For a realistic modeling study, dead and live loads were considered in the numerical study. Accordingly, the design was examined regarding the combination of the duct weight, insulation loads, and dust accumulation. The results obtained are given in Fig. 20. The connection plate section was exposed to a shear force of 327.3 kN and a moment of 16.1 kNm. Considering the safety stress for an 8.8 quality M20 bolt, the allowable load-bearing and the joint shear capacities were calculated as 59.7 kN and 358.2 kN, respectively. Deformation has occurred in the steel material before the shear-induced rupture of the bolts in all connections. Considering the joint and the axial forces on the bolts caused by the bending moment, we determined that the factor that initiates the collapse is not related to these insufficient strengths.

The tensile force on the RC column footings built over the existing foundation was calculated to be 1100 kN. The foundation-to-column dowels with a depth of 7-8 cm cannot meet this force. Considering the analysis results and the construction faults detected in the field study, it was evaluated that the structure did not have adequate seismic resistance. However, we decided that foundation-to-column dowels exposed to the tensile forces in the footings (forces lifting the foundation upwards) under service loads did not affect the collapse of the duct system.

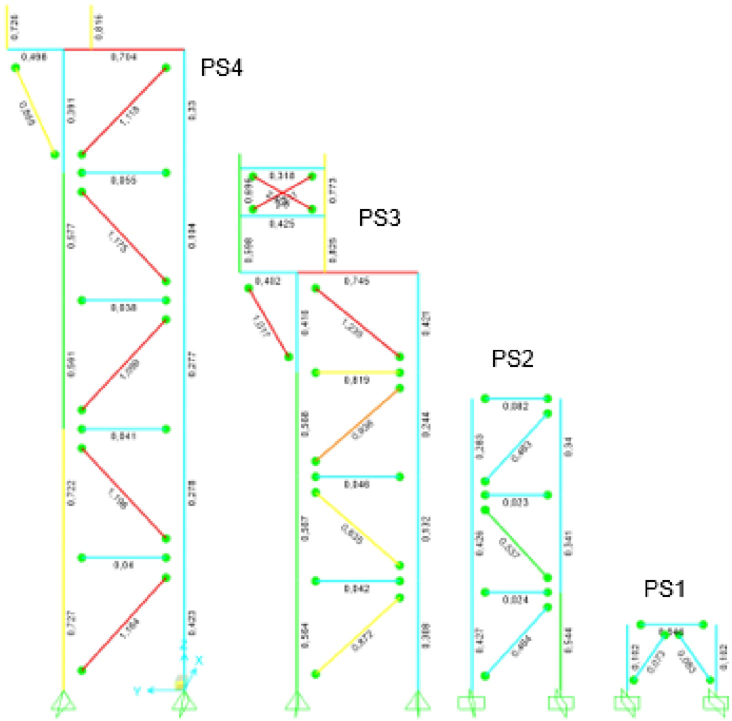


Fig. 19. Analysis results for the most unfavorable load combination

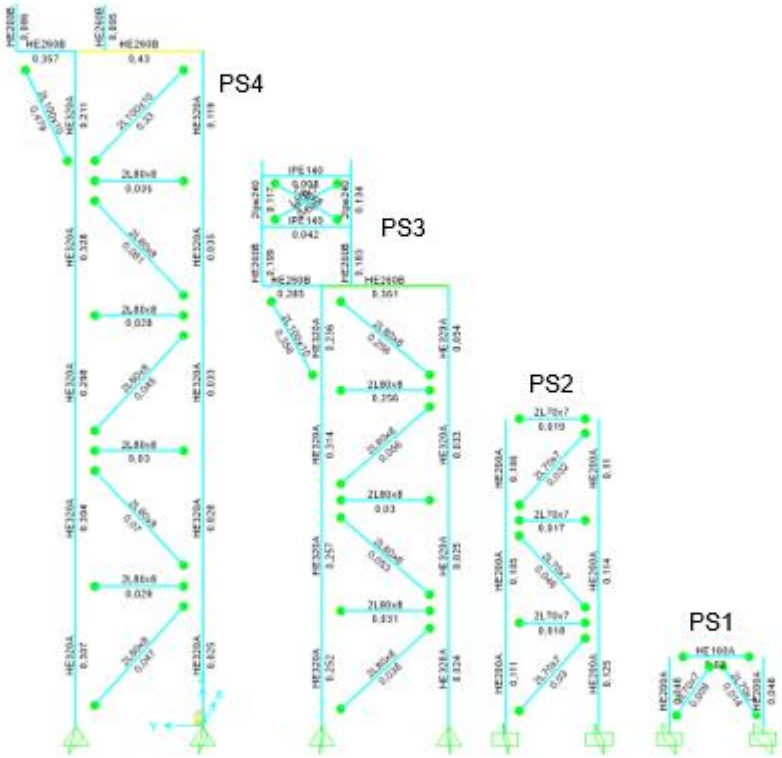


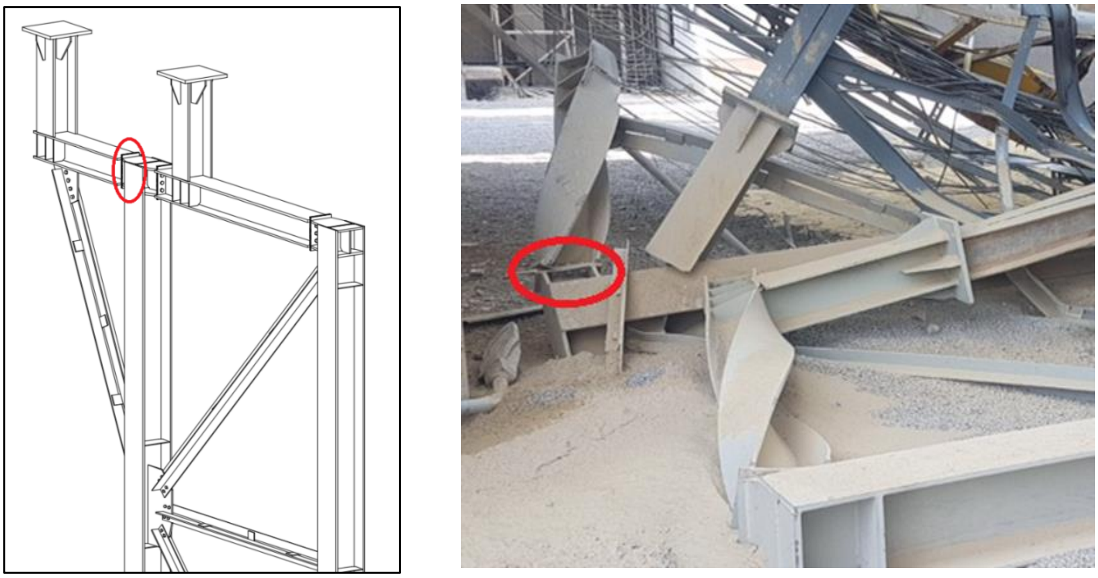
Fig. 20. Analysis results for vertical loading

The static project stated that 8.8 quality 6M20 bolts should be used at the joints of the horizontal HE260B element at the top of the PS3 and PS4 columns, but this choice is not structurally appropriate. This situation poses a risk to the load-bearing system, not only for seismic effects but also for vertical loads. However, to determine the bolt strength, yield stress can be used instead of allowable stress. In this case, bolt strength does not affect the collapse of the structure.

We determined that in the revised static project, the strength of the console placed to out-of-plane loads was insufficient. This joint exhibited only a hinge behavior.

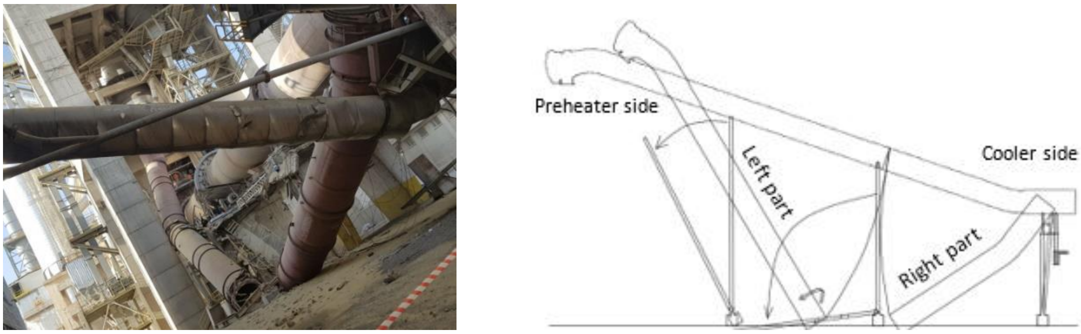
Since there was not enough data on the out-of-plane loads used in the design process, the analyzes could not be done in the 3D model, so a 2D model was developed and used in numerical studies.

Torsional behavior is likely to occur as a result of the lateral load on the column. Besides, if the bolts were subjected to moment loads, ruptures must have occurred. However, we observed that the bolts did not rupture when the collapse started. The bolts behaved rigidly allowing the console beam to rotate approximately 150 degrees (Fig. 21). The post-collapse examinations of the positions of the duct parts revealed that the columns PS3 and PS4 overturned towards the preheater tower, whereas the columns PS2 and PS1 tilted in the opposite direction, towards the clinker cooler unit. The distance between the broken duct parts on the ground was measured to be approximately 6 m. As the long piece of the duct (left part) fell, the RC console rotated about 90 degrees around its axis. However, the shorter piece of the duct (right part) seems to fall flat on the ground (Fig. 22).



a) b)

Fig. 21. Out of plane vulnerability of the console-beam connection. (a) The project, (b) Actual



a) b)

Fig. 22. (a) Post-collapse view of the plant, (b) Duct positions after the collapse

5. Conclusion and remarks

The current study examined the causes of a partial collapse that occurred in a cement facility just after two months of commissioning. The collapse occurred due to vertical loading without an earthquake or blast-induced effects. For examinations, fieldwork, review of the design project, and numerical analyses were carried out.

In general, a collapse may occur due to two reasons:

i. Construction practices contrary to the project conditions,
ii. Project design errors,

To determine which factor is the main reason for the collapse, a field study was conducted. In this fieldwork, the compatibility between the finished cement plant and the design projects was examined. Plus, the consistency between the static and mechanical design projects was also discussed. With numerical analysis, it was determined whether the design met the relevant regulatory requirements. The fieldwork, review of the projects, and numerical analysis revealed that both of the above-mentioned causes of collapse were present. To put it another way, construction practices contrary to the project conditions were carried out, there were inconsistencies between the static and mechanical design projects concerning loads and structural members, the current static design project does not meet the current regulatory requirements, and a wrong design was made. Therefore, to identify the actual cause of the collapse, the pre- and post-collapse positions of the ducts were examined. Accordingly, two potential reasons were considered. First, the reason for the collapse was due to the overturning of the PS3 column. The second is the removal of the pin between the ducts. Assuming that the collapse was triggered by the collapse of the PS3 column, the columns PS2 and PS1 would have to be tilted towards the preheater tower; because the system can move only towards the preheater side since the other end of the duct was roller support. However, the actual situation was different. The columns PS2 and PS1 tilted towards the cooler unit. Accordingly, we determined that the duct slipped out of its pin and the free duct ends moved vertically. In other words, we found that the actual cause of the collapse was due to a wrong pin application.

In conclusion, the findings of the present study indicated that a project and corresponding design should be prepared by an expert team, a perfect consistency between static and mechanical design projects should be ensured, and effective audit practices should be carried out at all stages of the construction. Otherwise, not only financial losses but also human life losses may occur.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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