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CONCRETE SPALLING IN A SLIP-FORM CONSTRUCTED INDUSTRIAL CHIMNEY

ODSPOJENIA BETONU W KOMINIE PRZEMYSŁOWYM WYKONANYM W TECHNOLOGII ŚLIZGOWEJ

Abstract Slip-forming of industrial chimneys requires a high level of quality control in many aspects of the technology. This includes reinforcement positioning in the cross-section, concrete mix design and placement, formwork slip velocity and stability in high winds, as well as jack rod movement control during construction. This paper uses an example of a concrete spalling in a 175 m tall, reinforced concrete industrial chimney located in the eastern part of United States. Spalls were discovered during the first two winters after construction. All the spalls occurred at the top 18 m of the chimney shell and were clustered within a 60-degree quadrangle of the circumference facing south-west. Investigation included visual inspection, non-destructive testing (NDT), sample coring, and laboratory testing (strength and petrography). Using NDT techniques, a delamination was detected in the same general area as previous spalls. Similarly to the majority of the spalls, the delamination was directly centered over jacking rods embedded in concrete suggesting jack rod movement due to high winds during construction. Additional factors which likely contributed to formation of delaminations include low early age strength of concrete as well as localized discontinuities (cement lumping and segregation) resulting from concrete mixing and placement in cold weather conditions. Subsequent development of spalls at preexisting delaminations was likely caused by cyclic freezing and thawing, possibly accompanied by post-construction high-winds.

Streszczenie Budowa kominów betonowych w technologii ślizgowej wymaga wysokiego poziomu kontroli jakości w wielu aspektach, jak lokalizacja zbrojenia w przekroju konstrukcji, dobór składu betonu, metoda betonowania, prędkość ślizgu form i ich stabilność w silnym wietrze oraz kontrola przemieszczeń prętów ślizgowych w trakcie budowy. Niniejszy artykuł oparty jest na badaniach przeprowadzonych w celu określenia przyczyn odspojeń betonu w 175 metrowym kominie elektrowni położonym we wschodniej części Stanów Zjednoczonych. Odspojenia zostały wykryte podczas pierwszych dwóch zim po zakończeniu budowy. Wszystkie defekty wystąpiły w górnych 18 m komina i były skupione na powierzchni komina skierowanej w kierunku południowo-zachodnim stanowiącej 60-stopniowy wycinek obwodu komina. Analiza objęła inspekcję komina (ocenę wizualną i badania nieniszczące) oraz badania laboratoryjne pobranych próbek betonu (wytrzymałość na ściskanie i ocena petrograficzna). Stosując metody nieniszczące stwierdzono obecność delaminacji w tym samym obszarze komina, w którym wystąpiły poprzednie odspojenia. Jak w przypadku większości poprzednich uszkodzeń, środek delaminacji pokrywał się z położeniem pręta ślizgowego zabetonowanego w ścianie komina, co sugeruje przemieszczenia prętów ślizgowych pod wpływem silnych wiatrów występujących w trakcie budowy. Dodatkowe czynniki, które prawdopodobnie przyczyniły się do utworzenia delaminacji (i konsekwentnych odspojeń) to niska wczesna wytrzymałość betonu oraz zlokalizowane nieciągłości materiałowe (zbrylenie cementu i segregacja betonu) związane z betonowaniem komina w warunkach zimowych. Następujące tworzenie się ubytków betonu w miejscu powstałych delaminacji było prawdopodobnie spowodowane cyklicznym zamrażaniem i odmrażaniem oraz silnymi wiatrami występującymi po ukończeniu budowy komina.

1. Introduction

1.1 Overview of Slipform Technology

Slip-forming of industrial chimneys requires a high level of quality control in many aspects of the technology. This includes reinforcement positioning in the cross-section, concrete mix design and placement, formwork slip velocity and stability in high winds, as well as jack rod movement control during construction. Due to the fast-pace nature of the slipform technology, freshly placed concrete remains in forms for a relatively short period of time.

For instance, in the chimney construction project discussed in this paper, the slip velocity was 2.2 cm per 3.5 minutes, whereas the formwork height was 2.4 m. This translates into about 6 hours of stay-in-form time for any given section of concrete. During this time, concrete not only needs to set but also gain sufficient strength to support self-weight and wind loads. Such fast construction pace may present a particular challenge in cold weather conditions, whereby special precautions, such as use of set-accelerating admixtures, need to be taken to address low rate of concrete strength gain.

1.2 Background

This paper presents an investigation of five concrete spalls, four external and one internal, from a recently built, 175 m tall, reinforced concrete chimney shell located in the eastern part of United States. The subject chimney is circular in plan, with constant external diameter of 22.9 m, an overall height of 183 m and 175 m tall exterior reinforced concrete shell. Construction of the reinforced concrete shell took place between October and December. The shell was constructed with continuous concrete casting using a slipform method. In this method, the forms are supported by vertical tubes, referred to as jacking rods, protruding from previously cast concrete. The chimney shell was cast using thirty jacking rods supporting the forms along the wall perimeter. Three types of jacking rods were used, with diameters of 2.7, 3.4 and 7.3 cm, and respective capacities of 2.7, 5.4 and 20.0 tonnes. Jacking rods are continuous from ground to the top of the chimney and are composed of segments that are 3.7 to 4.6 m in length, internally threaded and connected by externally threaded studs. With the vertical progress of the construction, the embedded in the concrete jacking rods were left in place. At the upper half of the concrete shell, the rods were designed to be at the center of the 34.6 cm thick wall. While the design wall thickness in the lower half of the shell was greater (57.2 cm), the jacking rods were kept nominally at the same distance from the external surface as in the upper half.

An external and internal layer of reinforcing steel was placed in the cross section of the shell, each layer consisting of horizontal and vertical 16 mm bars spaced at 300 mm in the lowest chimney section. With increasing elevation, the bar size gradually increases to 32 mm, whereas the bar spacing gradually decreases to 200 mm used in the top section. Additional reinforcement was placed around the louvered openings present primarily in the top section of the chimney. The specified concrete was a 31 MPa mix with 19 mm maximum aggregate size, 100 mm slump, 5 percent air content and water-cement ratio of 0.43. In addition to water-reducing and air-entraining admixtures used in all concrete batches, set-retarding admixture and hot water were used during construction of the top 82 m of chimney shell.

Four concrete spalls were discovered during the first winter after construction and an additional spall occurred during the following winter. All spalls occurred in the top 18 m of the chimney and were clustered within a 60-degree quadrangle of the circumference facing south-west (Fig. 1). The spalls reportedly occurred directly over jacking rods, as illustrated in Fig. 2. Of the four external spalls, three were near louvered opening corners. The spall characteristics are summarized in Table 1. Although spalling took place before the chimney operation began, relatively large spall size raised a question of hazard for the power plant personnel.

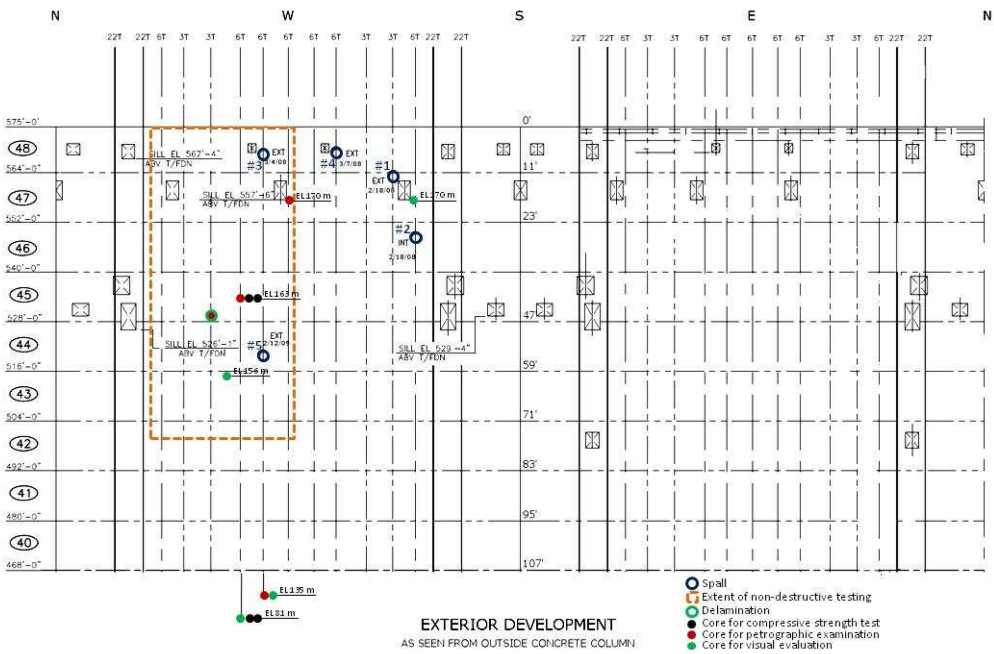

Fig. 1. Locations of spalling (#1 - #5), delamination, non-destructive testing and coring (Note: only top 143 m shown for clarity).

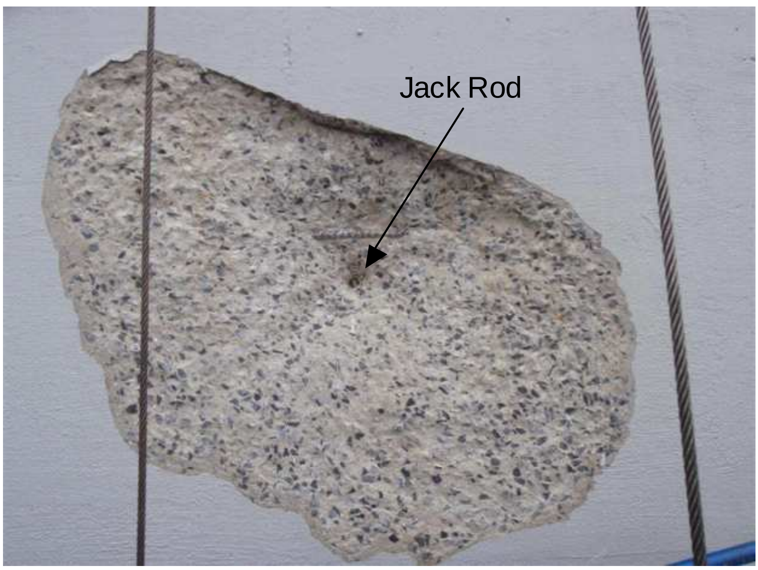

Fig. 2. Spall number 5 (approximate spall size is 1.2×0.6 m).

Table. 1. Summary of spalling.

Spall #	Date of Discovery	Approx. Elev. (m)	Dist. from Top (m)	Approx. Size (m)	Face	Jack Rod Type	Location Details
1	2008-2-18	172	3	0.8×0.9	Exterior	2.7 tonne	Near opening
2	2008-2-18	168	7	1.8×0.8	Interior	5.4 tonne	
3	2008-3-4	173	2	0.9×0.9	Exterior	5.4 tonne	Near opening
4	2008-3-7	173	2	0.9×0.9	Exterior	5.4 tonne	Near opening
5	2009-2-12	159	16	1.2×0.6	Exterior	5.4 tonne	At jack rod connection

1.3 Objectives and Scope

The primary objective of this investigation was to determine the root cause of spalling and to assess the likelihood of future spalling. The scope of the investigation included review of available documentation (structural plans, construction sequence, concrete test reports, weather data and spall photographs), field inspection (visual inspection, non-destructive testing and sample coring), and laboratory testing (compressive strength and petrographic examination).

2. Field Inspection and Testing

2.1 Site Visit

The inspection involved the following activities: visual evaluation of the exterior chimney surface from the ground level and from a swing stage, visual observation of the interior chimney surface from internal platforms, non-destructive testing of the exterior chimney surface and sample collection from the chimney exterior.

The internal chimney surface was visually examined from internal walk-way platform at about half-height and near the top of the shell. No evidence of spalling was visible in the examined areas. The exterior surface of the chimney located on the south-west side (the quadrangle of prior spalls) was visually examined from the swing stage during non-destructive testing and coring operations (discussed in the following section of the paper). Visual examination was performed over an area of 62 m^2. No evidence of spalling was visible in the examined area of the chimney exterior.

Surface anomalies such as voids and cold joints were observed throughout the interior and exterior surface of the chimney shell. While these anomalies did not contribute to the spalling, they are indicative of problems with the quality of concrete mix and construction practices.

2.2 Non-Destructive Testing

Non-destructive testing was limited to the general area of spalling and its extent included the top 23 m on the south-west side of the chimney exterior (Fig. 1). Impact echo (IE) and ultrasound shear wave techniques were used for detection of potential defects such as delaminations, honeycombing or cracking present in concrete. Ground penetrating radar (GPR) was used to determine locations of reinforcing steel and jack rods.

Impact echo testing was conducted during three swing stage drops extending 23 m from the top of the concrete shell. Each of the three drops covered an area spanning two adjacent jacking rods (i.e., testing was conducted along a total of six different jacking rods). Within each drop, impact echo readings were taken at three points spaced vertically every 1.8 m starting 0.9 m from the top (13 different elevations). Two of these points were at approximate jack rod locations determined by a plumb bob dropped from the top of the parapet where the rod locations were visible. The third point was located between these two points at an equal distance from jack rods. The resulting total number of IE test points for each swing stage drop was 39.

At one of the NDT points, a 0.3×0.8 m delamination was detected using IE and confirmed using the ultrasound shear wave instrument. GPR evaluation revealed that the center of delamination was located over a jack rod. The maximum depth of delamination was determined to be about 9 cm, which corresponds to the location of exterior reinforcement.

2.3 Sample Coring

Twelve cores were obtained from the south-west side of the chimney exterior. Four cores were taken for compressive strength testing, four cores (included the core taken at the delamination) were extracted for petrographic examination and four cores were obtained for visual evaluation. The core locations along with designations are shown in Fig. 1. In addition, the concrete surface inside each core hole was evaluated.

2.4 Petrographic Examination

Petrographic examination was conducted on four cores in accordance with ASTM C 896 [1]. Concrete in each of the cores was found to be air-entrained with estimated air contents ranging from 2.5% to 4.5%. The air-voids were not uniformly distributed in the concrete in all four cores. Similarly, the coarse aggregate particles in each of the cores were not uniformly distributed from the exterior to the interior surfaces (Fig. 3). The non-uniform distribution of the air-voids and coarse aggregate was due to improper or incomplete mixing of the concrete.

Fig. 3 (left) shows a section of the core obtained at the delamination detected using NDT techniques. The delamination (visible as crack) extends through cement paste (rather than aggregate particles) which indicates fracture development at an early age of concrete.

In addition to non-uniform aggregate distribution, one of the cores contained two dark brown-gray areas at approximately 25 mm and 70 mm from the exterior surface, as shown in Fig. 3 (right). These areas were very hard and contained high content of entrapped air and of lumps of unhydrated portland cement. These cement lumps as well as non-uniform aggregate distribution were likely the result of improper batching sequence of concrete ingredients while using hot water in the concrete mix [2].

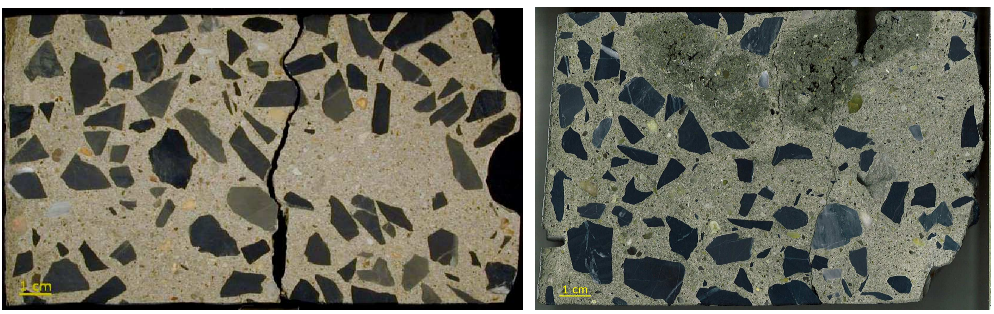

Fig. 3. Core sample cross-sections (left side of core sections indicates chimney shell exterior).

2.5 Compressive Strength Testing

Compressive strength testing was conducted on four cores in accordance with ASTM C 42 [3]. Two cores were obtained from the elevation of 163 m, which was identified to represent the coldest ambient temperature that the concrete encountered during placement. Two cores were extracted from the elevation of 81 m, which was determined to be well below the section of the low temperature exposure during placement.

The average strength for two cores obtained at elevation 163 m was 34.2 MPa, whereas the average strength for two cores taken at elevation 81 m was 33.4 MPa. Since these strength values were comparable, it was concluded that the low temperature during placement did not compromise the long-term strength. However, these strengths only slightly exceeded the required 28-day strength value of 31.0 MPa. Considering that the strength was measured almost two years after construction, the 28-day strength was certainly appreciable lower. In addition, the measured strength value is somewhat inflated by lower than the design value of the air content. In other words, 2.5-4.5% air content was determined from petrographic examination, whereas 5.0% was nominally required for the specified strength of 31.0 MPa. Finally, placement of concrete in the winter (i.e., low temperature) conditions resulted in low rate of strength development, particularly at the early ages of concrete. In summary, low strength of concrete likely contributed to formation of delaminations and subsequent spalling.

3. Failure Mechanism

3.1 Root Cause of Spalling

Detection of a delamination with similar characteristics (comparable size and location over jack rods) to the investigated spalls suggested that the mechanism of delamination formation is independent of, but prerequisite for, the actual spalling event. Thorough analysis of collected data suggested that formation of delaminations was the result of a combination of several factors, all of which are, directly or indirectly, attributable to construction of the top section of the chimney in severe weather conditions (high winds and low temperature).

Review of weather records revealed near – and below-freezing temperatures during construction of the top 23 m of the chimney. Low ambient temperature during and after construction had several implications on the concrete properties. First, exposure to low temperature led to low early-age strength of concrete. Significant reduction in the rate of strength development was likely exacerbated by presence of jack rods protruding from freshly cast concrete, which acted as heat sinks, thus further reducing concrete temperature. It is also low ambient temperature that necessitated use of hot water at the batch plant which, due to inadequate batching sequence, led to formation of cement lumps and segregation of aggregate from the cement matrix. Since the core taken at the delamination exhibited non-uniform aggregate distribution (Fig. 3 – left), these localized discontinuities are believed to have contributed to formation of delaminations.

Analysis of ground wind speeds (recorded at 10 m) during the time of construction revealed that wind speeds (fastest 5-second gusts) reached as high as 64 km/h during construction of the top 30 m. Wind speeds near the top of the chimney (170 m above ground level) are estimated to increase relative to ground speeds by a factor of 1.35 (per ASCE/SEI 7-05 standard [4]) to 1.48 (per CICIND Model Code for Concrete Chimneys [5]).

Two potential effects of wind on the chimney that are related to the concrete spalling are rapid evaporative cooling (potentially contributing to the cold weather effects described above) and displacements of jacking rods within newly placed concrete shell. Participation of jack rods in delamination formation is evident from the fact that the majority (if not all) of the spalls as well as the detected delamination were directly centered over jack rods. Because the jack rods protruded from the concrete and were directly connected to the formwork and associated platforms during construction, they were subjected to substantial wind loads. Jack rod movement due to high winds during construction exerted tensile stresses that exceeded the relatively low early-age tensile strength of concrete, thus leading to fracture development. A schematic illustration of wind-induced jack rod movement is shown in Fig. 4.

The depth of the detected delamination was approximately 90 mm which corresponds to the location of the external reinforcing mat representing a weak plane. Preferential development of such a weak plane would be expected in areas of reinforcement congestion, which explains occurrence of three spalls at the louvered opening corners (Fig. 1).

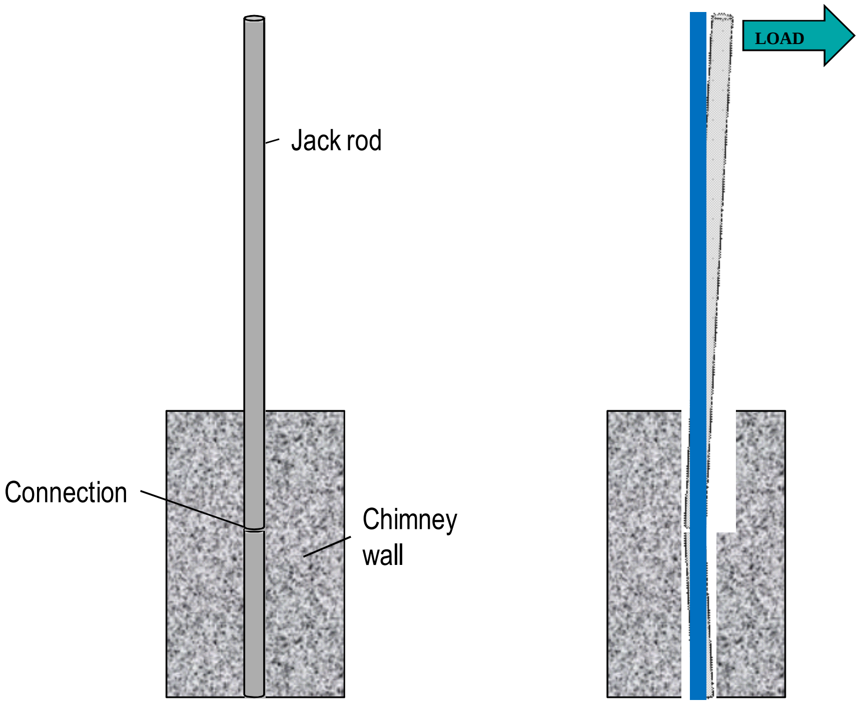

Fig. 4. Conceptual illustration of wind-induced concrete damage during construction.

3.2 Spalling Mechanism

Daily temperature records revealed that the maximum and minimum temperatures in the days leading up to the five spall discoveries frequently fluctuated above and below freezing. Due to the higher elevation, temperatures are likely lower than at the ground, particularly during night and morning hours. When exposed to sunlight, the south and west sides of the chimney can heat to temperatures greater than the measured air temperatures. These conditions make freezing and thawing more severe at the top of the chimney, and the cycles more prevalent in the south-west quadrangle [6].

Occurrence of all spalls in a 60-degree quadrangle facing south-west indeed suggests that development of spalls at preexisting delaminations was caused by cyclic freezing and thawing. It should be noted that all five spalls occurred before chimney operation began, which would warrant sufficient amount of moisture in the concrete from precipitation. Since operation began, hot gases in the flues enclosed in the shell heated and partially dried the concrete, effectively precluding freezing and thawing under normal operating conditions. Accordingly, existence of delaminations on the east and north sides of the chimney (not examined) is possible; however, due to limited number of freeze-thaw cycles prior to chimney operation, spalling never occurred.

Review of post-construction wind data indicated that the fastest 5-second wind speed recorded since construction completion (86 km/h at ground level) occurred on February 10, 2008, just one week prior to discovery of the first two spalls. A comparable gust was recorded on February 12, 2009, the day the fifth spall was discovered. Both of the gusts described occurred from the west (260°). Therefore, it is probable that the wind speed and direction assisted in dislodging the spalled concrete pieces.

4. Conclusions

Consideration of patterns common to the investigated concrete spalls and the detected delamination suggests that the mechanism of delamination formation is independent from a spalling event. Initial formation of delaminations was the result of a combination of factors attributable to construction in severe weather conditions, including high winds (which led to jack rod movement) and below-freezing temperatures (resulting in low early age strength of concrete, cement lumping and concrete segregation). Subsequent development of spalls at preexisting delaminations was likely caused by cyclic freezing and thawing, possibly accompanied by post-construction high-winds.

No evidence of imminent additional concrete spalling was found on the interior of the chimney, which is protected from precipitation and direct wind action. Since the flues enclosed within the concrete shell are currently operational, the chimney wall is dry and relatively warm, thus limiting the likelihood of future interior spalling resulting from freeze-thaw action. Nevertheless, it was recommended that an enhanced close-up visual inspection consistent with ASCE Class I inspection guidelines [7] be conducted over three years each spring followed by regular Class II inspections with a return period of three years.

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