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DELAMINATION IN A PRESTRESSED CONCRETE WALL – A MULTI-BILLION DOLLAR DISTRESS IN A NUCLEAR POWER PLANT

ROZWARSTWIENIE ŚCIANY Z BETONU SPRĘŻONEGO MULTI-MILIARDOWY PRZYPADEK W ELEKTROWNI JĄDROWEJ

Streszczenie Po 35-ciu latach eksploatacji elektrowni jądrowej w Stanach Zjednoczonych rozpoczęto wymianę generatora pary. Znajduje się on obok reaktora jądrowego w budynku ochronnym, który, jak prawie we wszystkich elektrowniach jądrowych USA, jest skonstruowany z betonu sprężonego jako cylinder z kopułą. Ponieważ zagęszczenie urządzeń i rurociągów wewnątrz budynku jest bardzo duże wyjęcie starego generatora pary i wprowadzenie nowego przez otwór drzwiowy przygotowany w konstrukcji okazuje się bardzo pracochłonnym i trudnym przedsięwzięciem. Stąd bardzo często praktykuje się w elektrowniach amerykańskich wycinanie na okres wymiany generatora większego otworu w ścianie budynku ochronnego. W opisywanym przypadku, podczas wycinania otworu (8×9 m) beton ściany cylindra (grubość 102 cm) rozwarstwiał się w płaszczyźnie przebiegającej w pobliżu płaszczyzny pionowych i poziomych kabli sprężających tj. około 20 cm od powierzchni zewnętrznej cylindra. Wielokrotne próby stabilizacji rozwarstwienia, poprzedzane intensywnymi wysiłkami obliczeniowymi nie dały satysfakcjonujących rezultatów. Naprężenia w w/w płaszczyźnie przy zmianach wynikających z prac budowlanych, a przede wszystkim rozprężania pojedynczych kabli, powodowały dalsze rozwarstwienia. Poziom ryzyka związany z lokalnymi naprawami bez przyjęcia zjawiska jako fenomenologicznego jest zbyt wysoki. Stąd rozpatruje się naprawa powłoki poprzez wprowadzanie konwencjonalnego zbrojenia radialnego, co wiąże się z ogromnym nakładem finansowym i trudnościami dostępu do powierzchni ściany w wielu miejscach, gdzie inne budowle przylegają do powłoki budynku ochronnego.

Abstract After 35 years in operation of a US nuclear power plant (NPP), the steam generator was to be replaced (steam generator replacement, SGR). The steam generator is located next to the reactor inside the containment structure which, as is typical to US NPP is a concrete cylinder shell with a dome constructed of prestressed concrete. In order to facilitate the removal of the old and installation of the new steam generator, an opening was cut out in the thick wall of the containment cylinder. A plane of concrete delamination followed closely by a plane of the tendon location was found in the de-stressed area of the wall. Efforts to stabilize the delamination process and provide a reliable repair solution failed. The estimated cost of repair exceeded the economic value of the reactor unit, and the owner decided on its decommissioning.

1. Introduction

1.1. Concrete as a major element of nuclear power plant structural reliability and safety

Key structures

The evolution of nuclear power plant construction techniques has resulted in today's unquestioned demand for a full containment structure over high radio activity systems.

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Concrete, initially conventionally reinforced and progressively prestressed, has become the structural material/method of choice. The governing assumptions have been related to its internal pressure and temperature handling ability, toughness against external impact, and low sensitivity to environmental deterioration processes. Indeed, the fleet of over 40 year old US nuclear power plants attests to the success in implementation of these assumptions. The most noteworthy and visible among the US nuclear power plant structures is the containment structure. Typically it consists of a cylindrical concrete shell, monolithically cast with a heavy concrete mat foundation and enclosed by a monolithically connected spherical dome (Figure 1).

Unique characteristics and expectations

The massive structure provided many challenges during the early stages of its development. Namely, the large dimensions of the monolithic structure heavily reinforced or elaborately prestressed, which assures high integrity and leak tightness. While some of the containment structures consist of primarily free standing steel pressure shield housed inside the concrete containment, often the steel container is fully integrated as a liner to the cast against the concrete containment structure. Thus, the need for understanding concrete curing temperatures and long term creep effects became even greater to assure the relatively thin steel liner was not subjected to excessive compression stresses leading to liner buckling. The thick wall of the containment structure required by the adopted design approach requires either a large concentration of reinforcement near the external surface of the conventionally reinforced structure or large post-tensioning cable conduits for a post-tensioned structure. The radial stresses being considered negligible often allowed for an assumption that no radial reinforcement was needed. That thinking was not satisfactory to authors of later-design and conventional radial reinforcement was placed tying the exterior surfaces of the shell structure.

The containment structure is not the only critical one in the nuclear power plant. A number of vaults, buildings, and conduits are built in the vicinity of the reactor/containment building. All those structures reduce accessibility to concrete surfaces of the containment and other auxiliary facilities. Any above ground inspection/repair is greatly impaired. The issue becomes even more critical when underground structures and foundations are in the need of inspection/monitoring/repair.

Environment

Massive structures of the nuclear power plant experience, due to their wall thickness, substantial temperature differences between the interior and exterior surfaces. Also, the humidity conditions can be very different. While the thick walls provide for low average temperature and/or moisture gradient, near surface gradients can be substantial due to exposure to rapid environmental condition changes. Nuclear power plants are typically located in the vicinity of a reliable water supply, as their needs for cooling water, heat exchanger water, and emergency cooling water are major. Thus, the structures are often placed in areas of high ground water conditions, brackish water or in close proximity to the sea shore. Portland cement used for the mixing of the concrete is particularly challenged when the surface of the concrete is exposed to such aggressive conditions. The combination of the surface stress imposed by localized high temperature and moisture gradient, and the demand for crack control pose a formidable challenge to the design team. The surface is to be close to crack-free; the cracks are to be tight so that environmental attack on the reinforcement and freeze-thaw damage are precluded.

1.2. Growing number of reported cases of NPP concrete distress and deterioration

The assumption could safely be made that concrete structures, which make up the main component of nuclear power plants, have received state-of-the-art engineering attention and would be sound and reliable for any reasonable time expectancy, and yet a number of recently identified problems in nuclear power plants in both the US and Europe indicate that second order effects or an inadequate level of investigation led to failures severe in consequences.

Recent reports by the United States Nuclear Regulatory Commission (US NRC)[1] discuss concrete degradation issues due to Alkali-Silica Reaction (ASR) at the Seabrook Nuclear Power Plant. Reportedly the plant concrete was produced with reactive aggregate which, over the last 30 years has caused sufficient surface damage to the finished surfaces to alert the authorities and initiate a fully-fledged investigation. The ASR is particularly present in underground areas of the structures exposed to ground water.

Another US NRC communication addresses laminar cracking in the cylinder of the concrete shield structure of the Davis-Besse Nuclear Power Plant in Ohio.[2] The delamination was discovered while preparing the shield building for the Replacement Reactor Vessel Closure Head. The crack was discovered during the hydro-cutting of a temporary opening in the 760 mm thick reinforced concrete shell. The delamination followed the external reinforcement layer (with about 75 mm concrete cover) for one to two meters around the cut opening.

In preparation for a steam generation replacement project at the Crystal River 3, Florida, NPP, hydro-cutting of an opening in the prestressed concrete containment structure was carried out.[3] A lamellar crack (delamination) parallel to the external surface and coinciding with the location of the prestressing tendons was discovered. The unstable delamination cracking was found unpredictable and difficult to repair and the unit was declared not economically viable to repair and subject to decommissioning.

2. Containment Building Wall Delamination

The 860 MWe pressurized water reactor (Figure 1) started commercial operation in 1977. In 2009 a refueling operation started which included the replacement of the two steam generators located inside the containment structure. The reactor system is housed inside a secondary containment structure providing safety in case of accidental heat and/or pressure releases from the reactor system. The Steam Generators are also located inside the containment.

Figure 1. Overall site view.

The containment structure is about 48 m tall, 20 m internal diameter, cylindrical prestressed concrete shell with wall thickness of 1100 mm, with a prestressed concrete, 900 mm thick dome monolithically connected to the walls, and with an interior 10 mm welded steel liner anchored into concrete structure. The concrete walls have vertical buttresses positioned at 60-degree intervals. The prestressing of the concrete was carried out in the vertical direction through 144 evenly spaced tendons, and in the horizontal direction with 282 hoop tendons. The horizontal tendons span 120 degrees between two buttresses. The horizontal tendons are placed in couples at 1-meter interval. The tendons are housed in 130 mm diameter conduits. The tendons are made of 163 wires 7 mm in diameter.

2.1. Delamination discovery

As was typical for the 1970's design, the replacement of the 500-ton steam generator was envisioned at the time of construction of the unit as being done via an access hatch. However, over time it was determined that the congestion of piping and equipment inside the containment structure, and the auxiliary facility density on the outside, would make the transfer of the steam generator very difficult, and a method was developed of cutting a temporary opening in the containment shale at a high elevation above the ground level. The planned opening was 8200×7600 mm (Figure 2). To start the cutting of the opening detensioning of tendons crossing the future opening area was carried out. Two tendons were detensioned using hydraulic ram, 25 tendons were detensioned using flame cutting. The concrete was then removed using hydraulic pressure.

Figure 2. Original access hatch with the temporary Steam Generator Replacement opening

Upon removal of the concrete using hydraulic jet demolition, a delamination running generally along the plane of the tendons was identified (Figure 3). The delamination, while initially thought to be limited to the immediate vicinity of the opening was found to cover nearly the entire area between the two buttresses between which the opening was cut. Moreover, when detensioning and re-tensioning was carried out in the repair effort, new areas of delamination in other bays were identified through ultrasound testing.

Figure 3. Delamination of concrete along the line of the prestress-tendons.

2.2. Analysis

Deformation survey of the entire area surrounding the temporary opening, and delamination mapping were carried out. Numerical analysis was carried out using non-linear finite element models of the entire structure, detailed model of the temporary hatch area, and micro-level model for the tendon and surrounding concrete. Indeed with accurate input of concrete properties and refined modeling of the conduits it was possible to reproduce delamination of the concrete coincidental with the weekend plane of the tendon location subject to transition from radial compression of the inward located concrete to radial tension of the outward located concrete. The deformation of the structure was beyond its over 30 years of operation and strongly influenced by long-term creep.

2.3. Economic risk management

The cost of the construction of the facility was $400 mln USD. The facility provided service for over 30 years. The replacement of the steam generators was a step towards the extension of the US NRC operating license beyond the year 2016, marking the end of the 40-year operating license issued initially for the generating unit.

The containment repair plans included numerous trials, both experimental carried on the structure and on full scale mock-up wall segments, and analytical consisting of large number of repair scheme and post-tensioning restoration scenarios. In the final conclusion a repair consisting of pin ties installed with epoxy bonding in the radial direction of the wall was considered a reliable and constructible solution. However, large areas of the containment structure external walls were not accessible because of attached buildings. The owner was told that the uncertainty as to how many such ties would have to be installed and how well they might provide constraint to new concrete delaminations upon re-post-tensioning of the structure might have a significant impact on the cost of the repair. Indeed, a probabilistically defined range of $1,500 mln USD (repair) to $3,400 mln USD (replacement). As a consequence of those very high numbers and with a large probable spread in the final cost, the owner decided to apply for permission to decommission the unit.

3. Summary and Conclusion

Designing of thick-wall reinforced or prestressed concrete containment structures creates opportunities for second order stresses to become a primary cause of distress under ordinary operational conditions. Temperature, shrinkage, and creep are the primary driver of those conditions. However, high gradient stress reversal from compressive to tensile causes conditions which can lead to split cracking and delamination such as observed in the described case. Torturous stress flow path should be avoided in those areas. The large diameter and closely spaced prestress tendon conduits created a plain of such discontinuity where the compressed inner portion of the cylindrical wall was pulling inwards on the external portion of the wall.

In conclusion, nuclear power plant primary safety concrete structures have to be subject to advanced design procedures far beyond those typical to similar structures primarily due to far-reaching consequences of safety concerns in case of observed cracking. The need for thorough evaluation of materials intended for concrete mix cannot be underestimated as shown in cases where mildly reactive aggregate after decades of operation have led to alkali silica reaction driven surface deterioration. The exorbitant cost associated with nuclear power plant construction is by no means a guarantee of perfect performance of the structures subject to long term effects of rheological and environmental changes.

References

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