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Forensic Engineering Evaluation of an Allegedly Deficient Steam Turbine Foundation

By Dhirendra S. "Sax" Saxena, PE (NAFE 586F)

Abstract

Forensic engineering as applicable to "construction materials evaluation" was used to investigate a condition where an alleged severe deficiency occurred during placement of concrete for a steam turbine generator (STG) structure in west central Florida. The owner questioned the integrity of the partially completed structure, and demanded removal/replacement of the structure. The author conducted a forensic investigation to determine whether the deficiency was limited to the surface, or if removal and replacement of the structure was warranted.

Keywords

Forensic engineering, concrete placement, honeycombing, corehole videography

Introduction

A forensic materials engineer is normally called upon to determine and evaluate the extent of damage to or deficiency of materials as well as to recommend corrective measures. In such investigations, the goal is generally understood early, as some type of known or suspected material performance has been reported that initiated the necessity for the investigation. Generally, the inspector and/or the forensic field professional collects data to better understand the most likely cause of the issue at hand.

Within civil engineering, qualitative procedures are used in practice areas ranging from geotechnical to materials engineering. Forensic engineering can involve an investigative program of materials, products, structures, or components that may have failed or do not operate or function as intended, thereby causing damage to property or triggering a questionable result.

During the construction of an STG structure within a powerplant complex in west central Florida, an alleged severe deficiency was asserted regarding concrete structures. A significant amount of concrete was cast into a total of eight structural columns with interconnecting overhead beams. Upon removal of the forms, a visual inspection revealed an objectionable condition in the form of concrete honeycombing, segregated aggregate, voids, and rock pockets. It was observed in a major portion of the 20-ft structure's height in most of the columns and beams, and appeared more severe in the lower, 8- to 12-ft, zone. Likely factors contributing to this condition ranged from exceeding the specified lift of deposited layer thickness during concrete placement to inadequate consolidation of placed concrete. **Figures 1** and **2** illustrate these conditions.

The project owner raised questions regarding the structural integrity and possible need for replacement/removal of this partially completed STG structure. The general contractor agreed to undertake a detailed investigation program to determine whether deficiency was limited to the surface. Additionally, this process would determine if the extent of any deficiency could be

Figure 1
Close-up showing honeycombing and segregation of concrete.

Dhirendra S. "Sax" Saxena, 4175 South Pipkin Rd., Suite 106, Lakeland, FL 33811; (863) 226-0612 (x 215); dsaxena@billerreinhart.com

Figure 2
Voids and rock pockets being cleaned by hydro-blasting.

addressed by repairing the voided areas or if removal of the structure was, in fact, necessary. Failure, or alleged failure, was defined by the project owner as an unacceptable difference between expected and observed performance. A three-stage investigative program, consisting of an internal/external condition survey, a field investigation and laboratory evaluation, and a remediation/restoration program, was undertaken.

Stage 1 Investigation

Stage 1 consisted of a pre-remediation survey (PreRS), encompassing an external and internal condition assessment.

<u>Condition assessment — external</u>

The first phase of the PreRS consisted of visually inspecting, logging, photographing, and documenting each of the eight columns to evaluate the deficiency at the surface and to detail the depth of voiding and honeycombing. The column located in the far northeast portion of the STG structure showed extensive honeycombing across the base. In addition, the underside of the crossbeam in the northwest portion of the STG structure, spanning between the two columns, showed honeycombing, segregation, and voiding.

<u>Condition assessment — internal</u>

The second phase of PreRS was carried out through a field program that consisted of the following elements.

Field coring and laboratory evaluation program. Part one of the internal condition assessment consisted of coring horizontally at 22 strategic locations (bottom, middle, and top sections of columns and one overhead beam spanning between columns). The entire field coring program consisted of the retrieval of a series of 2.75-in.-diameter cores from each corehole in 1-ft sections cored along the horizontal and vertical directions. A total of four or five core runs were retrieved from each horizontal corehole. In view of the very close spacing of steel rebars within the columns, the investigative forensic consultant decided to limit the core size to 2.75-in.- diameter. This was done to avoid any conflict with the existing steel during the coring operation.

A total of 66 cores were retrieved, sawed, trimmed, capped, and cured. Following adequate curing, these cores were subjected to compressive strength tests, which reported a 28-day average comprehensive strength of 4,960 psi.

Part two of the internal condition assessment consisted of petrographic examination of hardened concrete cores as per applicable standards (ASTM C865-14). These 2.75-in.-diameter cores were examined using a petrographic microscope to determine their integrity, quality, and constituents. The petrographic examination showed the paste/aggregate quality ratio, bonding characteristics, and any void system in the paste. It revealed the quality of the concrete to be adequately dense and bonding to be intact in major portions of the core with the exception of the surface where honeycombing was apparent. In general, the paste/aggregate ratio ranged from 35/65 to 60/40 with the average being 50/50. The water-cement ratio was interpreted to be 0.45 to 0.50 and was found to be acceptable and within the designed specification. Small spherical voids, typical of entrained air, were also noted to be present in the concrete. The concrete, which appeared to be adequately consolidated outside the noted voided areas, exhibited no evidence of detrimental internal paste-aggregate reaction.

TV video examination. Part three of the internal condition assessment consisted of a video examination of the interior surfaces of each corehole to confirm the concrete quality and identify any nonconforming features of paste/aggregate. This corehole camera survey was carried out utilizing a 1.5-in.-diameter Reese corehole video camera. It was equipped with a 90° side-viewing lens capable of rotating 360° and having a 7X magnification.

A detailed and thorough visual examination of the concrete in the interior portion(s) of all eight columns was performed by the petrographer. As the camera moved slowly through each of the coreholes, the petrographer

Figure 3
Insertion of the video camera through corehole near column base.

Figure 4
Petrographer examining the video screen for internal soundness.

documented and evaluated any unusual characteristic within the concrete as is illustrated in **Figures 3** and **4**. All the 22 core locations were examined to complete the internal condition assessment.

Packer tests. Part four of the internal condition assessment consisted of performance of Packer tests at six strategic locations. These locations were cored, and the cores were removed. The purpose of these Packer tests was to determine competency of in-place concrete as related to internal voids or large honeycombing that was not visible from the exterior and that might affect the structural soundness.

The Packer test was performed by sealing one or both ends of the cored hole into or through the structure and forcing water pressure into the core hole. Water was forced through a device comprised of a water meter capable of reading to 1/100th of a gallon and a pressure gauge capable of reading the pressure build-up with a shut off valve to close off and maintain pressure.

The pressure testing for this project consisted of forcing water under pressure through the device using the on-site water pressure, allowing the valve to remain open with a constant pressure of 30 to 50 psi and measuring the amount of water, if any, required to maintain the pressure in the cored hole at the maximum pressure achieved. Based upon a thorough evaluation of the Packer tests data, it was concluded by the forensic consultant that the internal concrete was competent. The STG structure layout identifying columns, overhead beams, core TV video, and Packer test locations is shown in **Figure 5**.

Stage 1: Conclusions and Remarks

The Stage 1 forensic investigation, consisting of a visual, video, and petrographic examination as well as results of compressive strength tests performed on cores revealed that:

- Structural soundness and competency of the concrete in the eight columns and interconnecting beams was substantially intact;

- The columns, as evaluated consisted of satisfactory quality concrete and retained the mass and integrity for which they were intended;

- The exterior honeycombing, segregation, and voiding, which in many cases exposed the rebar, was determined to be limited to the surface; and,

- Development and implementation of a restoration program was recommended to repair the external honeycombing and voiding, following removal of all loose and non-intact paste and aggregate from the affected areas by hydroblasting.

Therefore, it was concluded, recommended, and agreed upon by project team members that an extensive restoration was feasible and should be pursued as an acceptable and economic alternative.

Stage 2: Remediation/Restoration

Based on the findings and recommendations from the Stage 1 investigation, the retained consultant developed a remediation and restoration program to rehabilitate the STG structure to its originally intended design. This

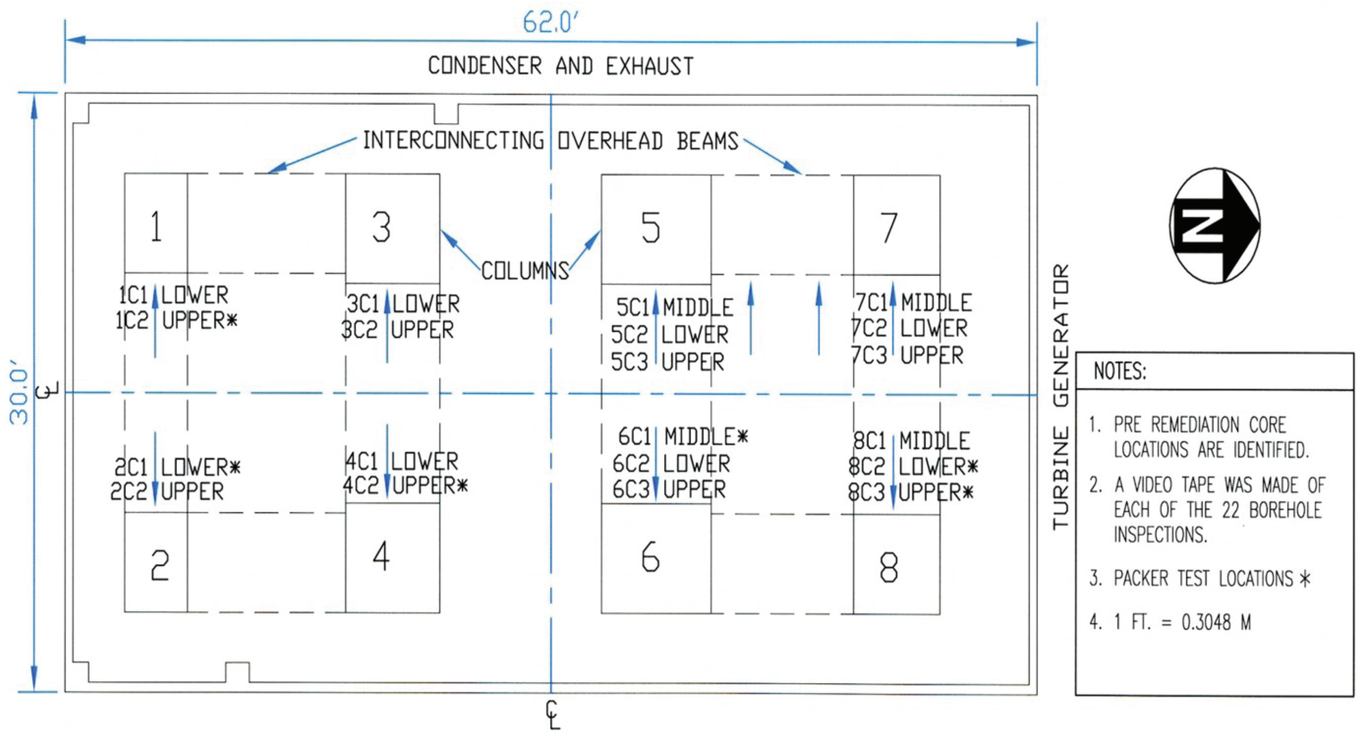

Figure 5
STG structure layout identifying columns, overhead beams, core, and Packer test locations.

remediation and restoration program consisted of:

1. Preparation of guideline specifications as well as a remediation and restoration program;

2. Chipping and hydroblasting of honeycombed and void areas;

3. Spraying or coating hydroblasted and dried surface using an acceptable bonding agent to create a bonding badge;

4. Forming, pumping, and pouring a high-strength grout mixture;

5. Pumping the grout from the bottom to ensure proper bonding and complete filling of externally accessible honeycombed, segregated, and voided areas;

6. Hand-troweling and packing into cored holes to ensure complete filling; and,

7. Reviewing proposals from various specialty subcontractors for the remediation and restoration program that would effectively restore voided areas as well as the surficial honeycombing.

During the entire Stage 2 restoration program, the retained consultant provided monitoring and inspection services for various operations including quality of the grout, forming, and the application procedures. Any defects in workmanship or grouting quality were immediately noted and corrected by the specialty subcontractor. Some overhead beam areas were determined to be lacking in bond as determined by visual separation in core specimens. These areas revealed insufficient bonding, and the specialty subcontractor was directed to chip the grout out for inspection and re-perform the repairs. A typical photograph showing sections of a pre- and postremediated column is shown in **Figure 6**.

Stage 3: Post-Remediation Survey

The purpose of the Stage 3 post-remediation survey (PostRS) was to assure integrity and competency of the restored concrete columns and interconnecting overhead beams in the STG structure. The scope of work included:

1. A detailed visual inspection of the chipped and hydroblasted portions of the honeycombed and voided areas and a selection of a number of areas for coring;

2. Surveying repaired/restored areas;

Figure 6
View of exposed column with pre- and post-restoration areas.

Figure 7
Tensile test set-up.

3. Evaluation of the performance of the remediation program by recovering and testing cores drilled through repaired grout materials and original concrete of each of the columns at 14 locations;

4. Performing microscopic examination and evaluating the bonding characteristics of the original and grouted surface by conducting tensile strength tests.

The initial phase of the PostRS consisted of coring horizontally a total of 14 cores through the repaired grout/concrete bond in the upper and lower sections of each of the columns. These 2.75-in-diameter cores were removed and examined by petrographic analysis using microscopic examination. The microscopic examination of the concrete revealed the quality of the concrete to be excellent and bonding characteristics to be intact in a statistically significant portion of the cores.

A total of 14 core specimens were sawed, trimmed, capped, and cured. Following completion of curing, three core specimens were subjected to compressive strength and direct tensile strength tests at seven- and 28-day time intervals after restoration. The compressive strength average for the 14 core specimens at 28 days was 5,800 psi.

The core specimens were subjected to direct tensile strength tests (ASTM C496) and exhibited failure within the original concrete with the failure mode to be through paste and aggregate as illustrated in **Figures 7** and **8**. In addition, the average direct tensile strength values of the core specimens in remediated or restored areas compared favorably (i.e., equal or greater) with that of the original concrete core specimens. Failure characteristics were noted to be normal.

The STG structure layout showing areas exhibiting deficiencies and requiring remediation as well as the PostRS core locations is shown in **Figure 9**.

Concluding Remarks

- Following completion of the Stage 2 remediation/restoration — and based upon results of Stage 3 post-remediation survey and a thorough review of the remediation details — it was determined by the project owner that the repair of eight columns and associated overhead beams had been achieved satisfactorily.

- The final repair resulted in restoration of the STG structure to its originally planned and designed dimensions and design conditions, as depicted in **Figure 10**.

Figure 8
Tensile strength tested core.

- Application of forensic engineering principles was a key factor in restoration of the STG structure.

- Following satisfactory completion of the remediation program, the retained forensic consultant recommended acceptance of the restored structure to the client.

Figure 10
View of repaired STG structure.

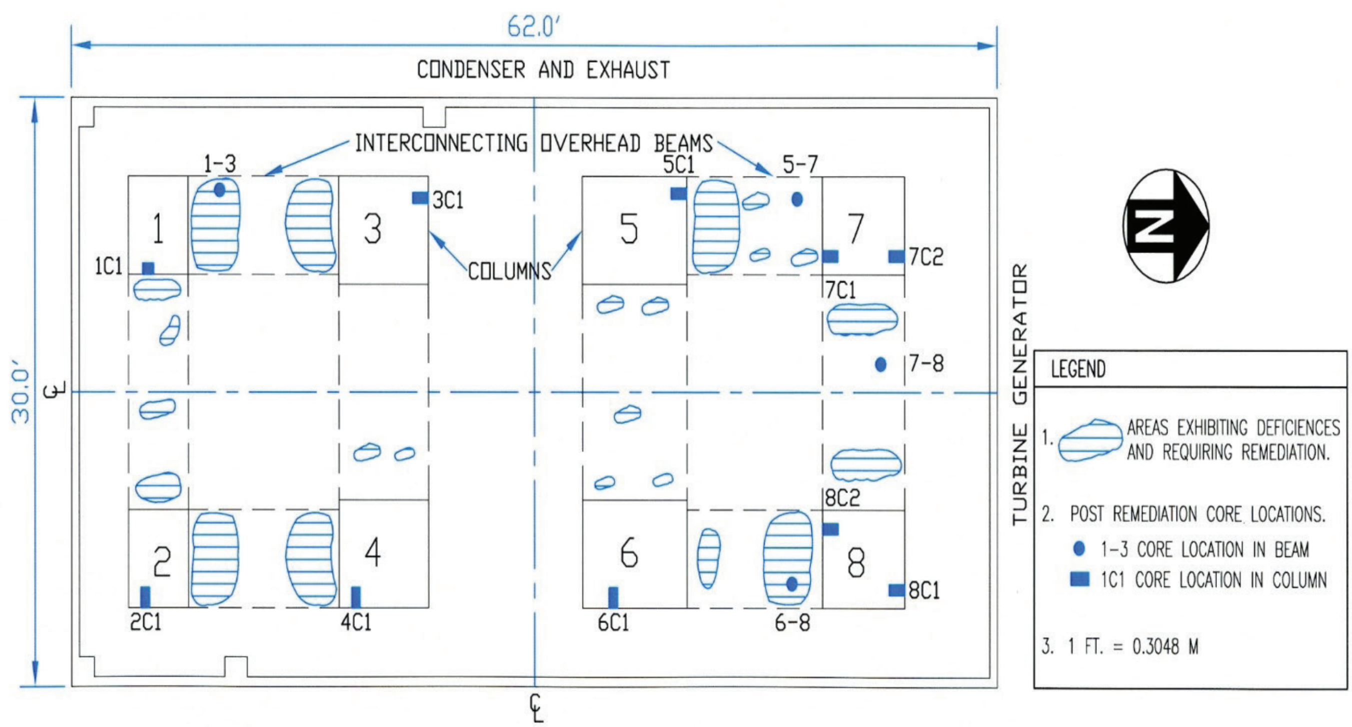

Figure 9
STG structure layout showing deficient areas and post-remediation core areas.

- A view of the restored structure is illustrated in **Figure 10**.

Acknowledgements

The opportunity to perform the services described herein provided an interesting exercise in the planning and execution of this unique project. The information herein is from a project where the author was involved as the forensic engineering and material testing consultant. It must be stated that the remediated and restored STG structure has been in operation for the last 20 years to the client's and owner's satisfaction. The author expresses his appreciation to the other project team members, including the general contractor, specialty restoration sub-contractor, and the petrography consultant.

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