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An Engineering View of the Statue of Liberty Restoration

Restauration de la Statue de la Liberté du point de vue de l'ingénieur

Die Restaurierung der Freiheitsstatue aus der Sicht des Ingenieurs

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SUMMARY

The restoration of the Statue of Liberty was completed in 1986, in time for its centennial celebration. This paper describes the original structural system, its history, the materials and its analysis and design. Also described are the studies, surveys, investigations and analyses conducted to determine the conditions existing and the repairs and modifications necessary for the restoration of the structure. Finally, the solutions considered for the long term preservation of the Statue are discussed, the decision-making process is described and the solutions implemented are presented.

RÉSUMÉ

La restauration de la Statue de la Liberté a été complétée en 1986, à temps pour la célébration de son centenaire. Ce document décrit la structure originale, l'histoire, les matériaux et l'analyse du projet. Sont aussi décrites les études, les mesures, les recherches et les analyses entreprises pour déterminer les conditions existantes et les réparations et modifications nécessaires à la restauration. Pour terminer, les solutions considérées pour la conservation à long terme de la Statue sont discutées, la démarche pour la prise de décision est décrite et les solutions retenues sont présentées.

ZUSAMMENFASSUNG

Die Freiheitsstatue wurde 1986 rechtzeitig zum hundertjährigen Jubiläum restauriert. Der Bericht beschreibt sowohl Originalkonstruktion, Geschichte und Baustoffe wie Analyse und Gestaltung. Ausserdem werden die Studien, Vermessungen und Berechnungen dargelegt, um den aktuellen Zustand und die notwendigen Reparaturarbeiten und Anpassungen zu bestimmen. Zum Schluss werden die für eine langfristige Erhaltung der Statue in Betracht gezogenen Vorschläge, der Entscheidungsprozess und die angewandten Lösungen geschildert.

1. ORIGINAL STRUCTURAL SYSTEM [8]

1.1 Structure of the Statue [1] [2] [5] [6] [7]

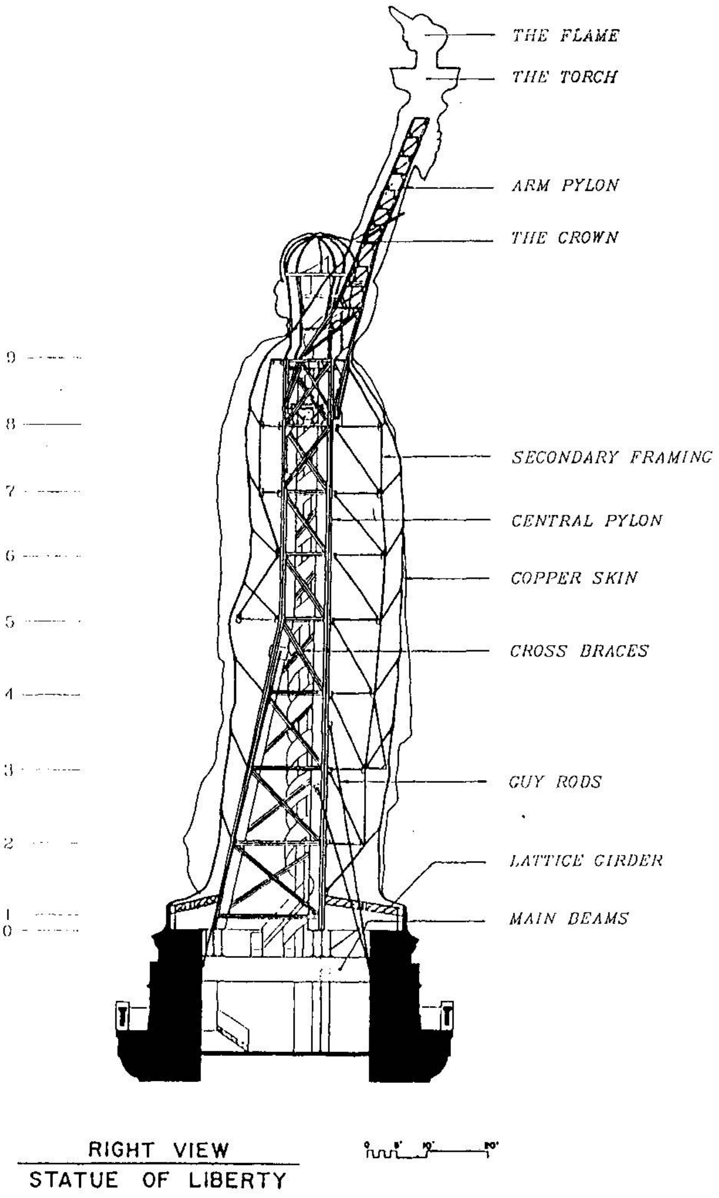

Fig. 1 The Structure of the Statue

Earlier monumental works in copper repoussè (the technique of hammering copper sheets in relief) supported on an iron armature was stabilized by mass masonry on the interior. An example of this is the colossal statue of St. Charles Borromeo constructed near Aroma, Italy, in 1697.

Eugenè Viollet-le-Duc, the first architect-engineer to work on Auguste Bartholdi's statue, Liberty Enlightening the World, conceived its structure as a series of sand-filled interior coffers. Viollet-le-Duc died in 1879 after only the torch, arm and head were built. Gustave Eiffel, the famous French bridge engineer, was called upon to complete the structure.

Eiffel's design for the structure was innovative for his time (Fig. 1). This unique system consists of a trussed central pylon and secondary framing to support the copper skin and iron armature through an assembly of sliding and articulated elements which permitted "breathing" of the Statue under thermal and wind loadings. The most ingenious aspect of his design is the concept of flat bars to connect the skin support system to the secondary framework. The steeply inclined bars are installed in compression and provide the resilience to allow adjustment to changes due to temperature and wind pressures. This design was also suited to the planned prefabrication in Paris and subsequent dismantling and re-erection in New York.

As innovative as Eiffel's concept for the structure was, his selection of the material for the structure, puddled wrought iron, had been used for centuries.

For the analysis of the pylon structure the force polygon graphical technique was brought to Eiffel by Maurice Koechlin, a student of Karl Culmann who developed the method at the Federal Polytechnic Institute in Zurich. Only the structure of the central pylon was analyzed for the static lateral loads used by Eiffel in the design of railway bridges.

1.2 Anchorage and Pedestal Structure

The pedestal (Fig. 2) is constructed of concrete of various mix designs. Above ground, the pedestal is faced with granite. At the time of its construction, the pedestal was the largest mass concrete structure ever built.

The anchorage system for the Statue was produced in the United States and consisted of two (2) levels of dunnage beams, the main beams at the top and the anchor beams located about 60 feet below. The pylon is anchored to the main beams. Transfer of the overturning moment from the pylon is made from the main beams to the anchorage beams through tie rods. The anchorage beams are embedded into the concrete walls of the pedestal structure at each of their ends, engaging sufficient concrete to stabilize the structure against overturning.

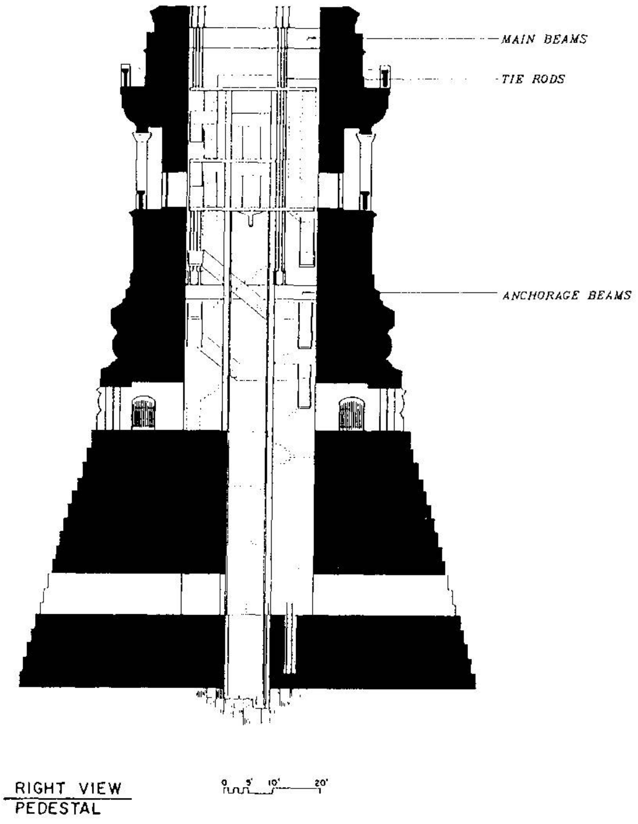

Fig. 2 Foundation, Pedestal and Anchorage

2. FIELD AND LABORATORY SURVEYS AND STUDIES

2.1. Surveys and Studies

The first phase of the restoration plan required a comprehensive survey and investigative program to identify the problems. This necessitated detailed field measurements to document the structure; field and laboratory studies including measurements of wind effects; measurements of stresses, displacements and frequencies and accelerations of the structural elements; and metallurgical studies to determine the properties and condition of the existing materials, including fatigue properties.

2.1.1. Field Tests

Some concern existed regarding the durability and fatigue exposure of the puddled-iron framework of the Statue, especially since it was noted that, by its nature, the material contained numerous inclusions, resembling cracks, which could act as "stress raisers." A program of inspecting the structure for fatigue problems was implemented. If fatigue is a problem in structures of this type, it initially manifests itself in cracking around rivet holes in areas of high stress. Therefore, rivets were removed in the high stress areas of the shoulder structure and the members were inspected visually with the aid of dye penetrants and magnetic particles. In addition, radiographic (X-Ray) inspections of select rivets, without removal of rivets, were made to determine if they were loose and to provide additional information on possible fatigue cracking around the holes.

2.1.2. Structural Instrumentation

To identify some of the hidden structural problems, the Statue was studied with the aid of strain gauge measurements[2] and accelerometers. The strain gauge measurements helped to identify two potential problems: weakness in the right shoulder and looseness of the anchorage of the Statue. The accelerometer measurements were taken to verify the results of the dynamic analyses in terms of the dynamic response of the Statue to wind, i.e., frequencies, accelerations and displacements. These measurements were correlated with wind measurements taken from an anemometer mounted on the torch platform.

2.1.3. Laboratory Studies - Material Properties

The puddled iron used in the framework of the Statue has a fibrous structure (highly directional) and contains many imperfections and slag inclusions. It was natural, therefore, that there was concern about the ability of the material to survive another 100 years, particularly from the viewpoint of fatigue. As a result, under the direction of Ammann & Whitney, an extensive program of testing was carried out by both Lehigh University and CETIM in Paris to determine the metallurgical and physical properties of the material. The tests undertaken by Lehigh University included tensile tests, Charpy V-notch tests (CVN), and fatigue crack propagation (FCP) tests on the angle and plate material removed from the Statue[3]. Tests undertaken by CETIM in France included fatigue tests in terms of stress range versus number of cycles to failure (SN).

3. STRUCTURAL ANALYSES [4]

3.1 General

Because of the historical importance of the Statue of Liberty, the preservation of evidence regarding its structural evolution was a high priority. A balance between structural adequacy and preservation needs, therefore, became an essential requirement of Liberty's rehabilitation. To meet this objective, the Statue was subjected to rigorous structural analyses including finite element analyses of its static and dynamic behavior, field measurements of its dynamical behavior, fatigue analyses of its remaining life, and the field and laboratory studies as previously described in Section 2.

3.2 Finite Element Model (Fig. 3)

The main pylon of the Statue, including the shoulder and the arm framing, was modelled as a three dimensional space truss. The geometric properties, including member sizes and makeup, were obtained largely from field reconnaissance surveys. Any stiffness contributed by the copper skin was conservatively omitted from the model; however, the influence of the "secondary" framework, which transfers the reactions from the skin to the main pylon, was included. The results of the dynamic analysis show that the two lowest modes, having frequencies of 1.66 hz and 1.90 hz, contribute over 95 percent to the response of the Statue under wind loads.

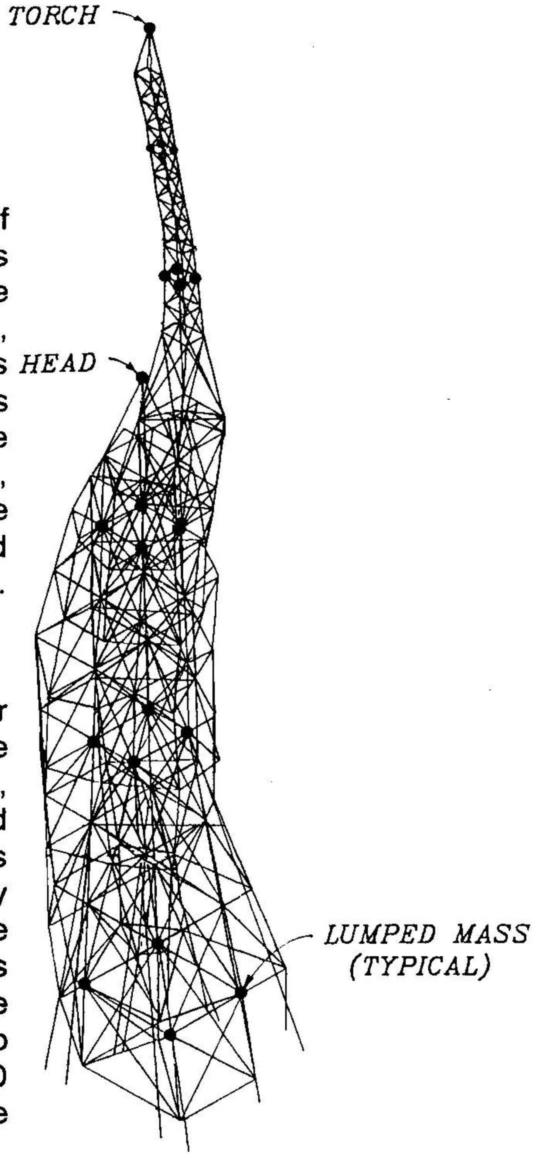

Fig. 3 Finite Element Model

3.3 Probabilistic Analysis

The significant environmental loads on the Statue are due to wind. Inasmuch as wind loads vary randomly in both time and space, it would have been inaccurate to apply conventional concepts in the analysis for wind loads. While such concepts usually result in safe and economical designs, the need for a realistic and reliable assessment of the fatigue life of the shoulder and main pylon prompted the application of probabilistic concepts in the calculations of the dynamic response of the Statue, and the attendant stresses, under the action of wind loading.

The maximum or extreme wind speed used for a survival analysis was based on a 100-year storm for the New York City Area. The turbulence characteristics of the wind, given in terms of the power spectrum of the longitudinal velocity fluctuations, was based upon observed data for exposures similar to those existing in the New York Harbor - mainly coastal areas.

Because the dynamic response of a structure is critically dependent upon its damping ratio, the damping in the statue was established by field measurement. The measured damping turned out to be favorably high, two percent of critical. This relatively high percentage of damping, compared to buildings and structures in general, is attributed to the unique manner in which the copper skin of the statue is attached to the main pylon. This attachment permits the skin to sway somewhat independently of the main pylon and thereby increases the overall damping through frictional hysteresis.

Aerodynamic damping, which is brought about by the wind induced forces relative to the vibration of a structure set into motion by the wind itself, amounted to about 0.5 percent of critical bringing the total damping ratio up to 2.5 percent.

The static response of the Statue to the mean wind loading component was obtained via standard static analysis methods using the finite element model. The additional dynamic response to wind gusts and vortex shedding was obtained from standard normal mode theory in conjunction with power spectral techniques. From this dynamic analysis, the ratio between the peak and mean response was found to equal 2.0. This results in an equivalent static wind speed of 128 miles per hour at the feet of the Statue and 141 miles per hour at the torch.

By comparison, Eiffel's loads equate to a static wind speed of 148.0 miles per hour, uniform with height. Although Eiffel's load is higher, the tributary area of the Statue in Eiffel's analysis is somewhat less than the as-built area, and the net effect is that the results computed by Eiffel for the main pylon are substantially similar to those produced by a 100-year storm used in the Ammann & Whitney analysis.

3.4 Fatigue Analysis

The analysis for fatigue effects consisted essentially of determining the number of cycles of different stress levels in various critical joints in the structure and combining these to determine the amount of fatigue life consumed in the past 100 years and projecting the life remaining when exposed to repeated cycles of wind. The distribution of the wind speeds used is based on Weather Bureau measurements for the New York City. In effect, then, the maximum stress levels were determined for a series of wind speeds each having a relative frequency of occurrence and duration.

It was found that winds in the range from about 30 to 50 miles per hour had the greatest influence on the fatigue life and not the greater stresses from higher wind velocities nor the more frequent stresses at lower wind velocities.

Apart from the laboratory tests for cyclic fatigue strength and resistance of the puddled iron to crack propagation, two factors in the fatigue analysis were of paramount importance in assessing the fatigue life of the Statue. The first was the stress concentration factor which is representative of the actual peak stress at the rivet holes. The second was the effect of the random exposure in determination of the equivalent number of cycles to failure for comparison with standard fatigue life curves based on traditional constant amplitude input. The stress concentration factor, based on traditional constant experimental data, was taken equal to 3.0.

Combining the exposure of the structure to the cyclic loadings with the results of the fatigue tests performed in the laboratory by CETIM and Lehigh University determined the projected life of the structure of the Statue. From a fatigue viewpoint, the structure has a projected life greater than 2,000 years.

4. STRUCTURAL REPAIRS

4.1 General

As determined from the investigations, studies and analyses, the problems that most necessitated the repairs and restoration of the structure of the Statue of Liberty were the weakness in the right shoulder and the head arches of the structure and galvanic corrosion of the armature.

4.2 Shoulder and Head Arches

The shoulder and head arch problems have existed since the Statue was constructed, a result of the misalignment of the head and shoulders from the originally designed positions, which created flexibility and overstresses in these areas. In the shoulder, the main deficiency was lack of torsional resistance which resulted in dangerous levels of axial stresses in critical members.

Several attempts to repair the weak shoulder were made in the past, most apparent of these is the unsuccessful attempt made by the U.S. Army in 1932. During the current project, two alternative solutions were proposed. The first alternative, termed the replacement scheme, consisted of removal of several members of the existing deficient shoulder and reconstructing the shoulder with a new truss, to achieve structural continuity to the main pylon. The second alternative, the repair scheme, adds several members to the existing structure to achieve the required rigidity and factor of safety. The history of the problem and proposed repairs of the shoulder are illustrated in Fig. 4.

Because the existing structure had historical significance, being as initially erected in Paris, it was decided to implement the repair scheme.

The repair of the head arches consisted of the addition of structural members to eliminate the eccentricities and restore the structural continuity as originally intended.

4.3 Armature

The problem of galvanic action between copper and iron was understood at the time of the Statue's original construction. An attempt was made to insulate the copper from the iron framework using asbestos cloth soaked in shellac. Although the insulation was a novel solution and worked for a period, with time the material deteriorated, became saturated with moisture and salts due to condensation and leakage in the marine environment of Liberty Island and, in the presence of this electrolyte, galvanic action took place.

Extensive studies were conducted to determine the most suitable material to replace the iron armature of the Statue. This meant determining a material that not only would be compatible electrically with the copper skin but would also have the same mass and stiffness as the iron armature it was to replace. The latter objective was intended to insure that the static and dynamic response would not be altered.

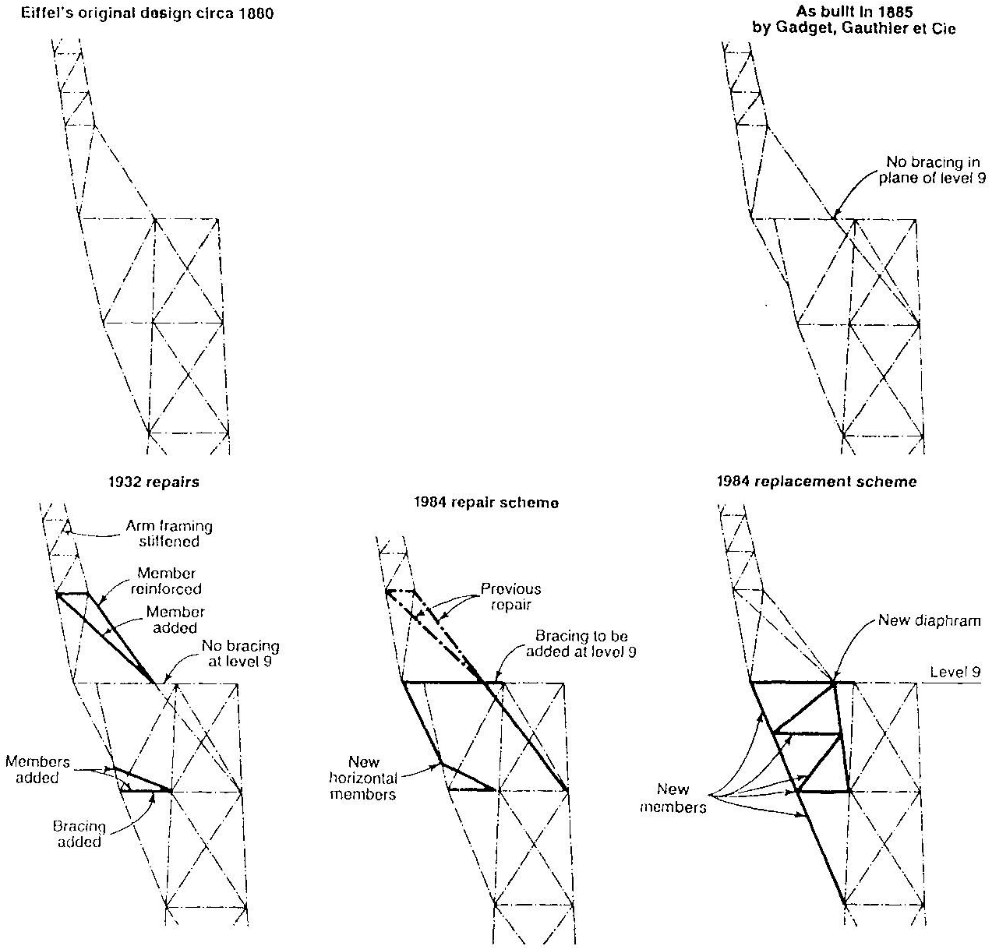

Fig. 4 History and Proposed Repairs of the Right Shoulder

To achieve these goals Ammann & Whitney recommended a ductile ferrous material either protected or inert. The National Park Service, in consultation with metallurgists, conducted extensive electrolysis tests and weathering tests on the several alternative materials including mild steel, copper alloys and various types of stainless steel.

Type 316L (UNS S31603) stainless steel became the material of choice for the armature replacement, since it had minimal galvanic reaction with the copper and duplicated the stiffness characteristics without a change in the dimensions or weight of the armature.

The material is difficult to fabricate without changing its mechanical properties and its corrosion resistant characteristics. This necessitated the development of special fabrication procedures, including forming, annealing and passivating the material[5].

As an added measure of protection, skived Teflon® was used between copper elements and the stainless steel armature bars. The Teflon® tape also acts as a lubricant to insure free movement of the copper skin and the structural support system.

5. SCAFFOLD [5]

To gain complete access to the entire structure, interior and exterior scaffolding was designed and erected by Universal Builders Supply, Inc., under the structural supervision of Ammann & Whitney. Because the Statue is unique and irreplaceable, the exterior scaffold was designed for a 100-year wind-recurrence velocity. In addition, a minimum distance of 1.5 feet was required between the scaffold and the copper skin of the Statue to allow for relative movement in severe wind storms. The resulting aluminum scaffold was an innovative, efficient and spectacular structure. The scaffolding and rigging greatly facilitated the execution of the construction operations and was a major factor in insuring the timely completion of the project.

The 81 feet square by 240 feet high structure became the tallest free-standing scaffold ever constructed.

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