Three-dimensional IT investigation of seismic distress in a large existing structure and development of remedial measures

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Abstract

This paper will describe a narrative and graphic overview of the unique forensic engineering methodologies utilized to resolve a critical structural distress scenario in a large hospital located on the island of Puerto Rico and will delineate the historic background and events leading to the detection and identification of structural weaknesses in this 85000 M² high rise structural steel hospital and the creative solutions to harden the structure against seismic forces; and prevent a potential catastrophic disruption of strategic healthcare.

It was imperative to develop an expeditious forensic investigation that would quantify the extent of distress, and develop remedial measures required to “harden” the structure to resist high seismic forces generated by slipping of the Caribbean tectonic plate. Hospital Authority Criteria maintained that operations of this facility would continue on a 24-hour, 365-day basis during the remediation process.

The structural remediation scenario was further complicated by the presence of asbestos containing spray-on fireproofing on the structural frame. Forensic investigators, implemented a comprehensive survey of the structure, interior geometry and a testing program using digital tools and three-dimensional structural analysis of this large structure using high speed computers and seismic applications of STAADIII and AutoCad software.

The results of the analysis indicated a potential for total failure of the facility. This paper details the forensic and engineering investigation methodologies for planning the remediation for this large scale project identifies the digital tools used for the forensic engineering analysis and the logic adopted for selecting the scenario of which identified a practical
solution to a complex issue and allowed this 2000 patient hospital to continue full operations during the seismic correction program.

1 Introduction

The opportunities for enhanced creativity and innovation in engineering practice have increased exponentially with advances in high-speed digital computers, sophisticated software and the advent of INFORMATION TECHNOLOGY SYSTEMS as a standard in consulting engineering offices.

These advances in INFORMATION TECHNOLOGY and the DIGITAL TOOLS that are a product of the advance have made sophisticated high-speed computer hardware and software economically available to all engineering disciplines as prices were reduced due to worldwide demand for new technology.

The use of these digital tools has offered unique opportunities for the extrapolation of the engineering creative process by enabling the engineering analysis of complex structures that were until the computer revolution, impossible to assess within practical limits.

The paper presents an excellent example of creative forensic engineering solutions and analysis using DIGITAL TOOLS to investigate a large existing hospital structure (16,000 structural members) located on the island of Puerto Rico. DIGITAL TOOLS were used in the multi-disciplinary physical survey, the development of as-built structural and architectural drawings, development of alternate scenarios for practical remedial solutions and development of construction drawings for implementing the "hardening" of the structure as well as other elements of this "STRUCTURAL CORRECTIONS" program.

2 Overview/history of the structure

The original design of the multi-story hospital was carried out in 1962 and the construction of the 85,000m² building was completed in 1964. The steel framed building rises ten stories above the ground. The lower four levels are 120 meters square (14,400 m²) and the upper seven levels are 45 meters square (2.025m²). The structural steel superstructure was designed and constructed as a three-dimensional structural steel ductile frame with column bays at 7.5 meters (each direction). The floor deck consists of a cast-in-place concrete composite slab system using a 75mm deep, metal deck. The deck spans between steel floor beams at 2.42 meters on center. The building is founded on deep pilings.

This full care teaching hospital holds a strategic command position in healthcare in the Caribbean basin. In addition to the 700 hospital beds within the hospital, the facility has a large outpatient population of nearly
2,000 persons per day. The central location of the hospital in Puerto Rico and its large size attracts patients from other Caribbean islands. In the event of a catastrophic event rendering this hospital inoperable, patients would be required to be airlifted to Mainland USA on a daily basis for healthcare. The caseload of over 2,000 patients per day generates a great number of visitors in addition to patients owing to the strong family values that exist on the island; each patient arrives at the hospital with an average of 1 to 3 family members. This creates a total of 4,600 patients and caretakers per day. It is quite evident that the authority must keep this strategic hospital in optimum operating status.

3 Detection of structural/environmental weaknesses

In 1995 the governing authority for the hospital was alerted to the potential distress that existed due to insufficient seismic resistance for the structure and other elements. An engineering firm was commissioned to carry out a preliminary study of the seismic capacity of the facility at that time. The results of the study indicated serious structural flaws on the building when subjected to code mandated seismic events.

The governing authority realized that measures must be taken to determine the magnitude of the distress and establish remedial measures to be implemented in order to provide a structurally sound facility. In addition to the structural weaknesses, the authority was made aware of additional safety and environmental shortcomings within the hospital systems. These factors included the presence of asbestos spray-on fireproofing on the structural steel (130,000m²), a lack of a fire suppression system and the requirement for additional emergency measures to maintain the hospital following a natural disaster.

4 Forensic investigation

O'Kon & Company was commissioned by the hospital authority to carry out physical and environmental surveys as well as a thorough computer-based, three-dimensional seismic analysis of the facility. The goal of the seismic analysis was to determine the capacity of the superstructure to resist code mandated seismic loadings generated by a ground acceleration factor of $\alpha = 0.35$. Furthermore, the commission included a survey of the seismic resistance of other hospital systems including HVAC, plumbing, electrical and water tanks, as well as capabilities to operate after a natural disaster (seismic or earthquake).

Furthermore, the commission required the development of a program of remedial measures to “harden” the hospital superstructure and implement
other critical environmental issues and emergency systems while maintaining the hospital in a status of full operation.

4.1 Planning the investigation

The use of DIGITAL TOOLS was optimized during the planning and implementation of the investigation in order to facilitate the program and accurately predict the extent of the distress. Planning was prepared utilizing the following outline.

4.1.1 Selection of a team of interdisciplinary professionals including: program managers, structural engineers, architects, mechanical, electrical, fire protection and environmental engineers as well as quantity surveyors and scheduling experts.

4.1.2 The development of the total SEISMIC CORRECTION PROGRAM, which included seismic structural corrections, removal of asbestos containing materials, new spray-on fireproofing, seismic bracing of electrical/mechanical systems, seismic resistant ceilings, new fire protection systems and interface with other hospital programs.

4.1.3 Research of the archives and collection of all original construction documents and as-built documents for all design disciplines both in hard copy and electronic form.

4.1.4 Survey of existing hospital facilities to develop a comprehensive as-built condition status using portable computers to input data on a continual basis.

4.1.5 Environmental sampling survey and testing to confirm the extent of asbestos containing materials.

4.1.6 Development of a complete set of interdisciplinary electronic based as-built documents.

4.1.7 Development of a massive three-dimensional, computer-based model of the superstructure of the hospital for use in the seismic analysis.

4.1.8 Review of performance of the as-built structure when analyzed using STAAD III software and appropriate seismic factors to determine the extent of distressed conditions in the structural system.

4.1.9 Development of alternate scenarios for remediation.
4.1.10 Selection of the remediation scenario that best suited hospital criteria.

4.1.11 Development of phasing, scheduling and construction documents to implement total remediation program for hospital.

4.2 Interdisciplinary survey/development of IT documents

An interdisciplinary team of project managers, engineers and architects carried out a survey of the physical elements of the hospital using DIGITAL TOOLS. The surveys included architectural, structural, mechanical, electrical, fire protection and environmental engineering studies. The field data was continuously input into laptop computers, which had been loaded with electronically based construction documents from hard copy archived drawings. The modified documents were used to generate a full set of interdisciplinary construction documents for the hospital systems. These updated the electronic documents were used to carry out the SEISMIC CORRECTIONS PROGRAM. AutoCAD Version 14 software was used to develop and recreate the composite structural drawings as well as other interdisciplinary drawings developed as part of the seismic corrections program.

4.3 Three-dimensional seismic analysis of the superstructure

The confirmed electronic documents were used to develop a large array three-dimensional mathematical model used in the computer-based analysis of the 16,000-member hospital superstructure. AutoCAD 14 software was used to develop and recreate the structural drawings as well as other inter-discipline drawings used in the seismic corrections program.

4.3.1 Three-dimensional model

The three-dimensional superstructure model was developed and analyzed using STAAD III software (Figure 1). The majority of the structural member designation used in the original construction had been outdated or replaced with new standard size nomenclature; therefore the 1962 American Institute of Steel Construction Handbook was used to accurately input prismatic data into the analysis. This operation superceded the current AISC data that selects or assesses modern steel member size nomenclature. Furthermore, the yield strength of the steel did not exceed 30,000 psi (207 x 10^6 N/m^2).

The large array mathematical model was analyzed using Pentium III, 500 MHz computers with 256k ram operating on a Windows NT network. The structural steel members were input as a moment resisting frame and finite elements were used to serve as the floor diagram in lieu of the
composite concrete floor deck in order to properly distribute lateral loads throughout the superstructure and as vertical concrete walls in the superstructure (Figure 1).

4.3.2 Loading cases for the superstructure
The hospital in the Caribbean exposes the facility to a double threat from environmental forces; it is exposed not only to high-risk seismic events but also to 250-kph hurricane forces. Therefore, the model was analyzed using a combination of vertical and horizontal loading cases including: dead load; live load; dead and live loads; dead and hurricane loads; dead and seismic loads; dead, live and hurricane loads; as well as dead, live and seismic loads.

4.3.3 Seismic resistance of as-built structures
To provide the authority with a concept of the seismic forces that could be safely resisted by the original design of the superstructure, the team was requested to determine the ground acceleration factors that could be within allowable stress limits. The analysis was carried out and it was determined that the structure could accommodate a seismic ground acceleration of $A_v = 0.12$. This is one third of the ground acceleration factors required by the governing code.

4.3.4 Seismic analysis of the as-built superstructure
The results of the seismic resistance capacity of the structural superstructure derived in item C3 (above) was a precursor of the poor performance that could be anticipated by the analysis of the superstructure using a seismic ground acceleration factor of $A_v = 0.35$.

The superstructure was then analyzed using $A_v = 0.35$ with the various load cases required by code. STAAD III using three methods of relative comparison to allowable stresses depicted the output of the analysis.

4.3.4.1 Graphics: A failure diagram in color was developed in three-dimension and in plan and elevation of the various frames. The failure diagrams indicate members within allowable stress limits in green, overstressed members are indicated in red. The failure diagrams indicated the vast majority of members to be red (overstressed) (Figure 1, 2, and 3).

4.3.4.2 Code check analysis: The program prints out the nomenclature of each member and states whether the member stresses are above or below code limits and will identify the code section violated. The narrative report was equally daunting with the majority of members indicating “failed” and the stress ration soaring to 3 to 4 times the allowable levels.

4.3.4.3 Post-query printouts: This printout (Figure 4) focuses on the individual structural member. The data includes the complete array of characteristics including member size length, stress levels, maximum forces
and ratio of actual stress to allowable stress and graphic printouts of the moments, stress, etc. in the beams. Printouts indicated that the majority of members were extremely overstressed, some were overstressed to levels that would be multiples of allowable stress levels (400 to 500%).

5 Selection of optimum remedial measures

An analysis and compilation of the overstressed members identified by the forensic investigation analysis was carried out; in order to develop a logical scenario for the seismic corrections program. The analysis included the member location, the magnitude of overstress levels, the potential remedial measures required to upgrade the member and the impact on hospital operations that would be effected by the total program. A phasing, scheduling and engineering program was developed to assess the input.

The engineering program management review indicated that a remediation program implemented for Scenario I would be improbable while maintaining hospital operations. Due to the large number of structural members that required remediation; including numerous elements that required total replacement due to radically insufficient capacity of that element. The investigation team advised the authority that the majority of the hospital must be partially if not totally closed during the seismic correction process due to the extensive remediation program. This hospital closing could be for up to four years.

5.1 Development of alternate remediation scenarios

The hospital authority determined that even a partial closing of hospital operations would render this actual healthcare mandate to be unmanageable. The alternate to closing would be the construction of a replacement hospital.

A program for a new replacement hospital facility was developed and a construction cost of $250,000,000 USD was determined. The authority declared this amount of capital expenditure was impossible due to budget constraints. Therefore, the authority requested O'Kon & Company to seek creative alternate scenarios that would:

5.1.1 Permit continuous uninterrupted hospital operations;

5.1.2 Permit construction integration with proposed hospital upgrade modification programs;

5.1.3 Implement remediation and seismic corrections for a total budget not to exceed $50,000,000 USD.
5.2 Identification of alternate seismic corrections: scenario II

The O'Kon & Company interdisciplinary team carried out a series of potential solutions to satisfy the new mandate. The obvious solution was identified and the simple solution was adopted as Scenario II.

The solution was based on elementary engineering mechanics vis-à-vis seismic force generator. It was determined that in order to reduce the lateral forces on the superstructure of the majority of the building, it would be necessary to reduce the mass of the upper part of the superstructure. Therefore, a series of modified three-dimensional models were developed; each subsequent model reduced the mass of the building by removing an upper floor until a minimum number of easily remediated structural members were optimized and the usable area of the hospital was maximized (Figure 5).

5.3 Seismic analysis of the modified superstructure: scenario II

The selection of the optimum geometrical configuration of the hospital building superstructure would serve as Scenario II and be recommended as the solution for the seismic corrections program.

The geometry of the superstructure was modified by vertical adjustment of the three-dimensional model. The geometrical structural adjustments were initiated by removing a series of tower floor levels from the model, analyzing the effect of the seismic forces on the modified geometry and assessing the results relative to the number of structural members affected combined with the relative loss of hospital floor space and attendant cost factors.

The following series of alternate geometrical models were analyzed and assessed to determine the model that expressed the optimum compromise between the extent of remediation, the loss of hospital space and the cost construction.

5.3.1 Trial A: Removal of floors 7, 8, 9

5.3.2 Trial B: Removal of floors 6, 7, 8, 9 (Figure 5)

5.3.3 Trial C: Removal of floors 5, 6, 7, 8, and 9

5.3.4 Trial D: Removal of floors 4, 5, 6, 7, 8, 9

The results of the analysis were assessed using deflection diagrams, failure diagrams, code review printouts and post query printouts.

The analysis of relative values for lost space, cost and remediation efforts were developed using a systems analysis spreadsheet. The results of Trial “A” indicated a high level of remediation and cost; the results of Trial “B” indicated a low level of remediation and cost; and the results of Trial “C”
indicated the minimum of remediation efforts and costs but required a loss of 2,022m² of additional floor space than Trial “B” (Figure 5, 6, 7 and 8).

Therefore, Trial “B” was selected as the optimum solution for the following salient factors:

5.3.4.1 Structural modification
The number of structural members that to be modified were less than 10% of the number required to be modified under Scenario I and the level of overstress was in the 25 to 40 percent range.

5.3.4.2 Hospital bed space
With Trial “B”, the hospital was able to retain 2,022m² on level 4; level 5 would serve as the new roof and provide mechanical space. However, the loss of levels 5 to 9 as hospital wards and the attendant 10,110m² in area must be replaced.

5.3.4.3 Cost implication
The cost of remediation of Trial B was slightly higher than Trial C, but the retaination of 2,022m² as well as the requirement for less replacement space made the choice of Trial “B” most attractive.

6 Seismic correction program

The selection of Scenario II was a success relative to continuation of hospital operations, minimization of structural remediation and optimization of capital cost for the program.

The solution to this unique program, which extended well beyond the strengthening of structure and remediation of life safety issues, was met with approval by the governing authority. The seismic program was estimated and budgeted at approximately $50,000,000 USD. The program was managed and led by the O’Kon & Company structural engineering managers, they served as leaders for a team of architects, interior designers, mechanical, electrical, fire protection, civil and environmental engineers as well as scheduling, phasing and quantity survey consultants.

The program included structural seismic upgrades, life safety, hospital bed space replacement, integration of hospital upgrade projects and demolition of five levels of the tower. This phased project will extend until 2005. Following are the salient elements programmed by this unique and creative engineering solution.

6.1 Replacement bed building

An ultra-modern two-story hospital bed building of 10,000m² in area located adjacent to the existing hospital.
6.2 Seismic corrections program with in interior existing hospital

The authority required phased integration of the seismic corrections program with individual hospital upgrade projects. The seismic corrections program includes the following salient elements:

6.2.1 Remediation of asbestos containing materials.

6.2.2 Seismic correction of distressed structural members.

6.2.3 Installation of new spray-on fireproofing.

6.2.4 Seismic support of mechanical/electrical systems.

6.2.5 Installation of new seismic resistant ceiling and lighting.

6.2.6 Installation of new projects to upgrade hospital departments.

6.3 Demolition of existing hospital tower

The removal of hospital tower floors 6 through 9 in order to reduce seismic mass (Figure 9, 10). The asbestos in the tower must be abated prior to demolition and demolition will proceed with maximized safety and a minimum of vibration and noise.

7 Conclusion

The seismic corrections program has been under construction for a year and will continue on a phased basis until the year 2005.

The implementation of this unique engineering solution to a critical life safety issue is a tribute to the integration of engineering creativity, information technology and a client who believed in the capabilities of her team of problem solvers.

However, the facility cannot be considered to be fully safeguarded until the existing tower has been removed and the remedial program completed.
3D MODEL OF SCENARIO I
Fig. 1

FAILURE DIAGRAM SCENARIO I
THIRD FLOOR
Fig. 2
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**STAAD QUERY SCENARIO I**

Fig. 3

**FAILURE DIAGRAM SCENARIO I**

FRAME 11

Fig. 3

* INDICATES FAILED MEMBER

Fig. 4
3D MODEL OF SCENARIO II

* INDICATES FAILED MEMBER

FAILURE DIAGRAM SCENARIO II
FRAME II

Fig. 5

Fig. 6
FAILURE DIAGRAM SCENARIO II
THIRD FLOOR

Fig. 7

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STAAD QUERY SCENARIO II

Fig. 8