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IKITELLI CITY HOSPITAL: PERFORMANCE-BASED DESIGN OF THE LARGEST BASE-ISOLATED BUILDING IN THE WORLD

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Abstract

Located in Istanbul, Turkey, on a gross building plot of 1 million square meters, Ikitelli City Hospital is the largest base isolated building in the world. The base-isolated Main Hospital Building consists of three specialty towers that are 15 to 18 stories tall, and six clinic buildings that are 3 to 5 stories tall. The towers and the clinics share a 5-story podium structure with approximate plan dimensions of 300m x 400m, sitting on top of 2,068 triple friction pendulum (TFP) isolators. The lateral load resisting system of the Hospital Building is special reinforced concrete shear walls.

Designed using ASCE-41 provisions, the target performance objective of the building is "Immediate Occupancy" at the Maximum Considered Earthquake level. To minimize construction costs and improve floor plan efficiency, the engineering team conducted a core-wall optimization study in which a total of 180 possible wall thickness configurations were evaluated. Concurrently, to allow the client to procure the most cost and schedule-efficient type of isolator for the project, the engineering team analyzed and evaluated the Building considering three types of isolators.

Non-Linear time history analysis of a building of this scale requires tremendous amounts of computation and produces multiple tera-bytes of data that need to be managed. To deliver the optimized design of the Building within a tight project schedule, it was necessary to implement cloud-based analysis and develop automated data processing tools. The paper serves as an introduction to the newly constructed Hospital, with a focus on the structural evaluation and design process.

Keywords: Performance-based design; Seismic isolation; Optimization; Cloud computing; Time-History Analysis

1. Introduction

Ikitelli City Hospital is located in the Başakşehir district of Istanbul, Turkey. The hospital consists of three specialty towers and six clinic buildings, all of which sit atop a common podium that is supported on 2068 Triple Friction Pendulum (TFP) isolators. The towers range in height from 15 to 18 stories, the clinics from 4 to 5 stories, and the shared podium comprises three levels of basement parking (Fig. 1**Error! Reference source not found.**). With a footprint of over 116,000 m^2 and a floor area of over 942,000 m^2, Ikitelli City Hospital now holds the record as the world's largest base isolated building.

The hospital building was designed to achieve ASCE 41 [1] "Immediate Occupancy" performance criteria under Basic Safety Earthquake-2 (BSE-2N), a very rare earthquake event. To assess the seismic performance of the structure, nonlinear time history analysis was conducted using software LS-DYNA per ASCE 7-10 [2]. The draft version of the Turkish Seismic Design Code (2016) [3] was also used where applicable. Seven three-dimensional ground motion records were used in conjunction with analysis models using either upper or lower bound properties for the isolators. This resulted in 28 distinct time-history analyses on the final building model.

Additional studies conducted before finalizing the building design included: (1) a concrete wall optimization study in which a total of 128 different wall thickness configurations were tested, and (2) an isolator type and layout optimization study in which a total of 5 LS-DYNA building models with various isolator type and layout combinations were built and subjected to the full suite of nonlinear time-history analyses for complete performance-based evaluation. These studies helped the client choose the optimal isolator type and layout from cost, performance and schedule perspectives, and resulted in optimization of concrete volume.

To run multiple suites of analysis on these various models, and to post-process the results in a timely fashion, use of digital tools, both for generation of the models and post-processing of the results, as well as cloud computing, were implemented.

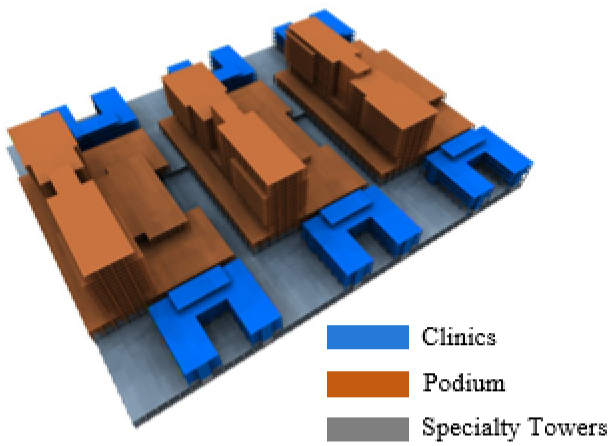


Fig. 1 – Ikitelli City Hospital

2. Seismic Hazard

The project site is located in a region of high seismic hazard that has been subjected to numerous earthquakes of moderate to large magnitude throughout history (Fig. 2). The ground motion history on the site constitutes moderate and large magnitude earthquakes every 50 and 300-years, respectively. Apart from the 1999 Kocaeli Earthquake, the region was not subjected to a large magnitude ground shaking in the 20th century. This atypical pattern has raised the concern that the region is due for a large magnitude earthquake at any time.

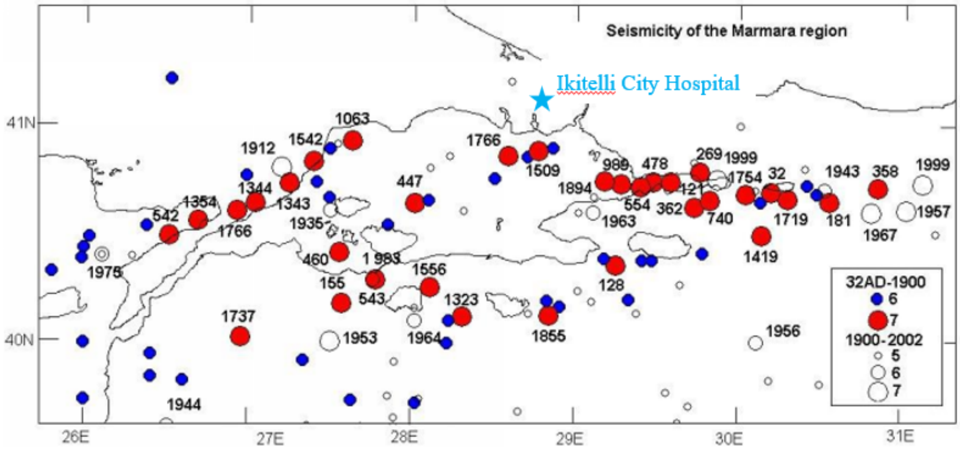


Fig. 2 – Past earthquakes with Magnitude greater than 5 within the Marmara region

Seismic design parameters are provided in Table 1. Site specific response spectra and the BSE-2N level ground motions used in analysis are provided in Fig. 3.

Table 1. Seismic design parameters

NEHRP Site Class	**C**
S_{MS}	1.150g
S_{M1}	0.820g
S_{DS}	0.750g
S_{D1}	0.510g
Distance from fault	< 24 km

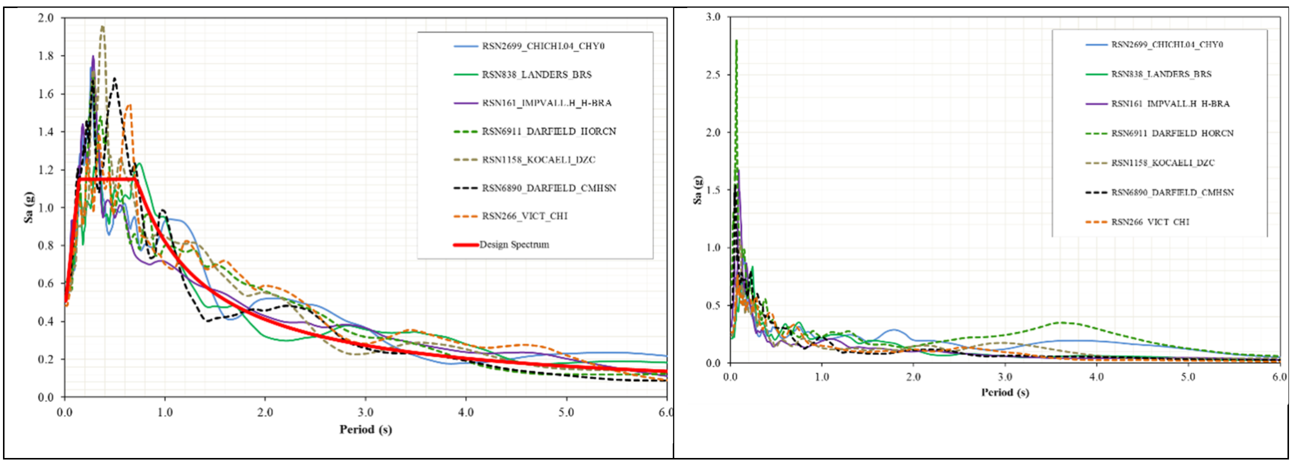


Fig. 3 – BSE-2N Horizontal (top) and Vertical (bottom) site-specific spectra

3. Acceptance Criteria

A performance-based design process following ASCE 41-13 [1] was used for the design of the structural components in the building. Where ASCE 41-13 did not provide specific acceptance criteria (such as axial strains), the draft version of the Turkish Seismic Design Code (2016) [3] was followed (Table 2). Gravity load resisting components and the isolation plane framing, i.e., concrete pedestals and girders supporting the isolators are designed to remain elastic.

Table 2. BSE-2N level acceptance criteria for deformation-controlled actions

Deformation-controlled Actions	**Acceptance criteria**
Lateral drift	1%
Confined concrete compressive strain limit	0.0035
Reinforcement tensile strain limit	0.01
Coupling beam plastic rotation limit	1%

4. Core Wall Optimization

The lateral load resisting system of the superstructure consists of special reinforced concrete shear walls in both directions. Due to the size of the project, concrete volume optimization was of utmost importance with the aim to minimize construction cost and improve floor plan efficiency at the same time. The optimization was performed using an automated model generation and analysis process in Grasshopper. Grasshopper is a visual programming language that runs within the Rhinoceros application.

Nine different wall groups (represented in different colors in Fig. 1) were identified based on similarity in plan geometry and wall height, and five different thicknesses were considered; 400, 500, 600, 700, and 800mm based on structural and architectural constraints. Given nine wall groups and five thicknesses, one would get approximately 2 million different wall thickness layouts mathematically. This includes combinations that are structurally not stable or practical, such as increasing wall thicknesses with elevation. To eliminate the impractical layouts from the total number of possible combinations, the following restrictions were implemented: (1) Top-most wall groups should be as thin as possible since they don't have a significant contribution to the lateral stiffness of the building (2) Bottom-most wall groups should be as thick as possible since they contribute most to the lateral stiffness of the building, and, (3) Variation in wall thickness from one level below to the level above to not exceed 200mm for ease in construction. These restrictions reduced the possible number of wall thickness layouts from 2 million down to 180.

The analysis software chosen for this optimization study was Strand7 due to its API features. 180 fixed-base Strand7 models were created through use of a script developed in Grasshopper. The process followed is summarized in Fig. 5. Modal analyses were conducted for each of the 180 models, and the modal results were extracted into CSV files which were then uploaded onto a database. The parameter that was being tracked between the fixed-base modal analyses was the fundamental period of the structure. To ensure dynamic decoupling exists between the isolators and the superstructure, a target fixed-based period of 1.75-seconds was chosen. The Strand7 model which satisfied this target with the least amount of concrete quantity was taken as the optimum solution.

A web-interface was developed through which all the modal analysis results and the wall thickness layouts could visually be seen (Fig. 6). This helped engage the client in the decision-making process.

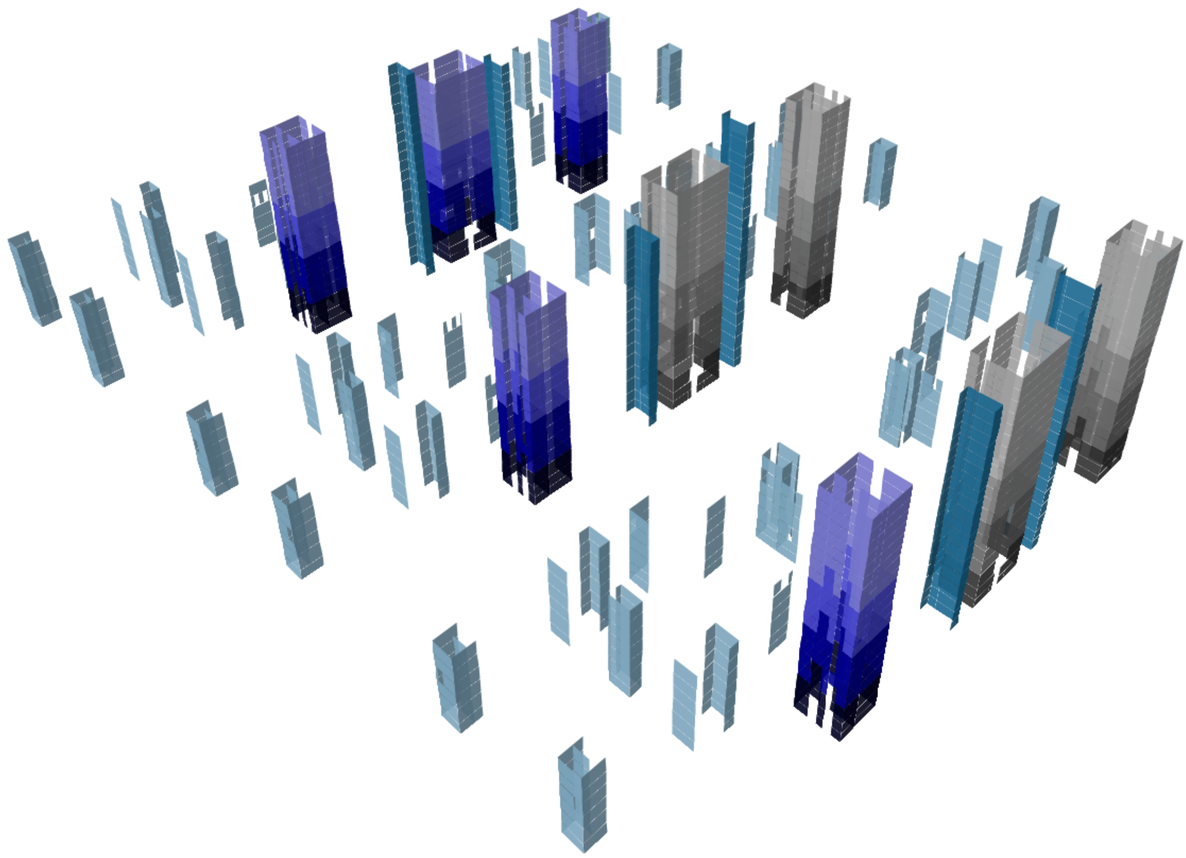


Fig. 4 – Concrete walls in the building

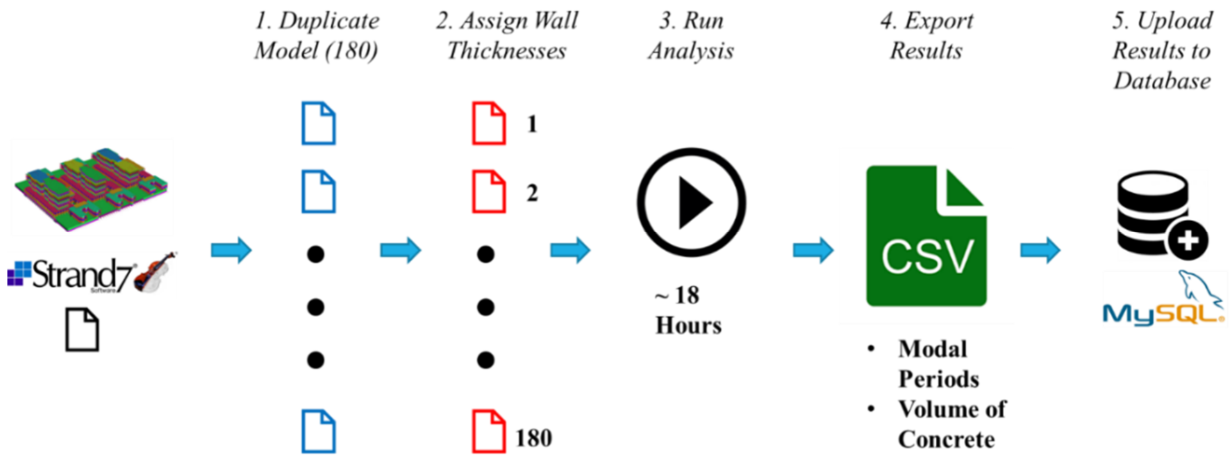


Fig. 5 – Wall optimization workflow

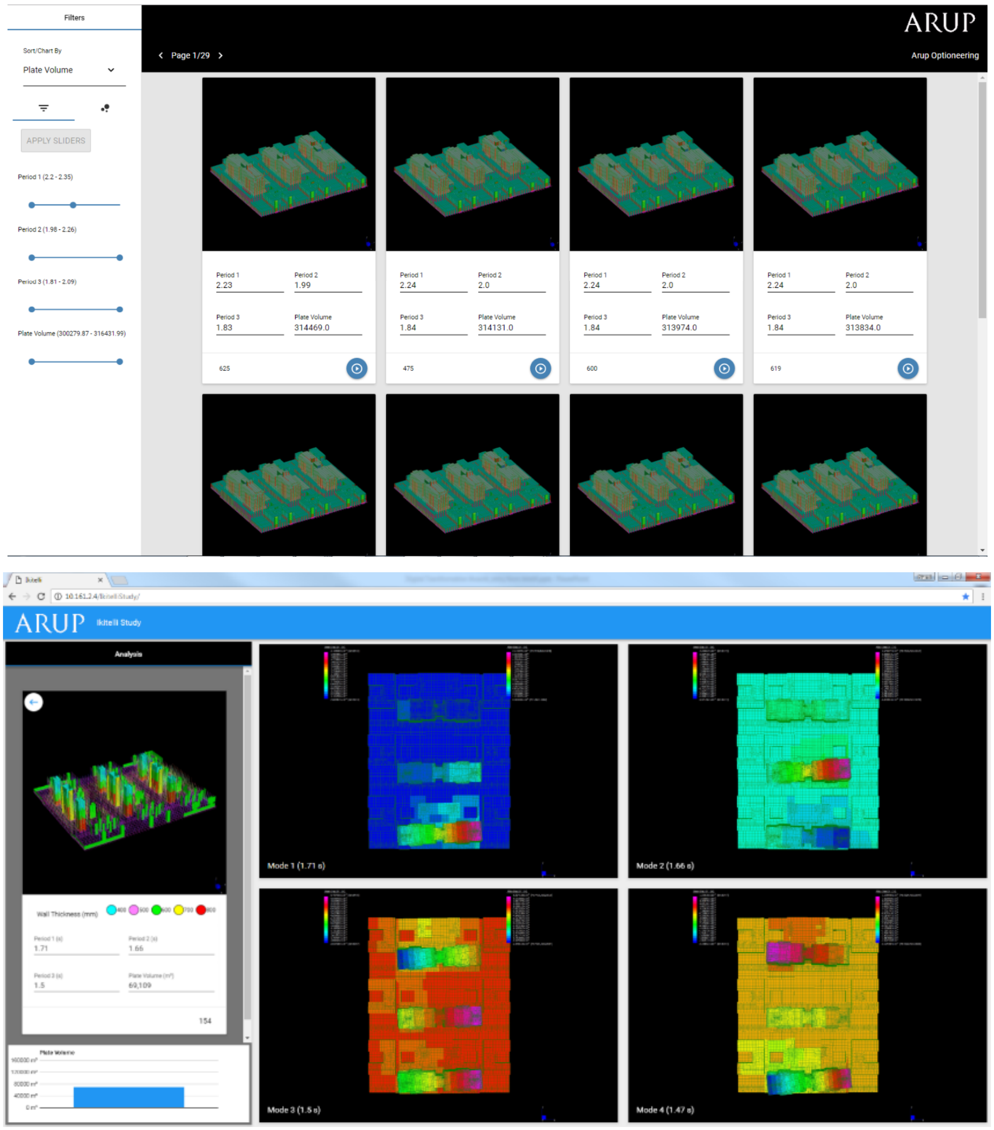


Fig. 6 – Screenshots of the web-interface used for concrete wall optimization study

5. Nonlinear Model

LS-DYNA was the chosen software for nonlinear analysis (Fig. 7**Error! Reference source not found.**) due to the large library of material models, the ease with which pre- and post-processing could be automated using custom-built components in Grasshopper, and because of the speed with which these complex models could be run on the cloud. Since LS-DYNA models can be read as simple text files with specific formatting, it is feasible to code components that read various inputs and format the data appropriately to be used in the model. Using centerline data from Revit and spreadsheets containing information on geometry, wall thicknesses, and reinforcement ratios, the model could be quickly generated using Grasshopper and visualized in Rhinoceros before being written out in a text file.

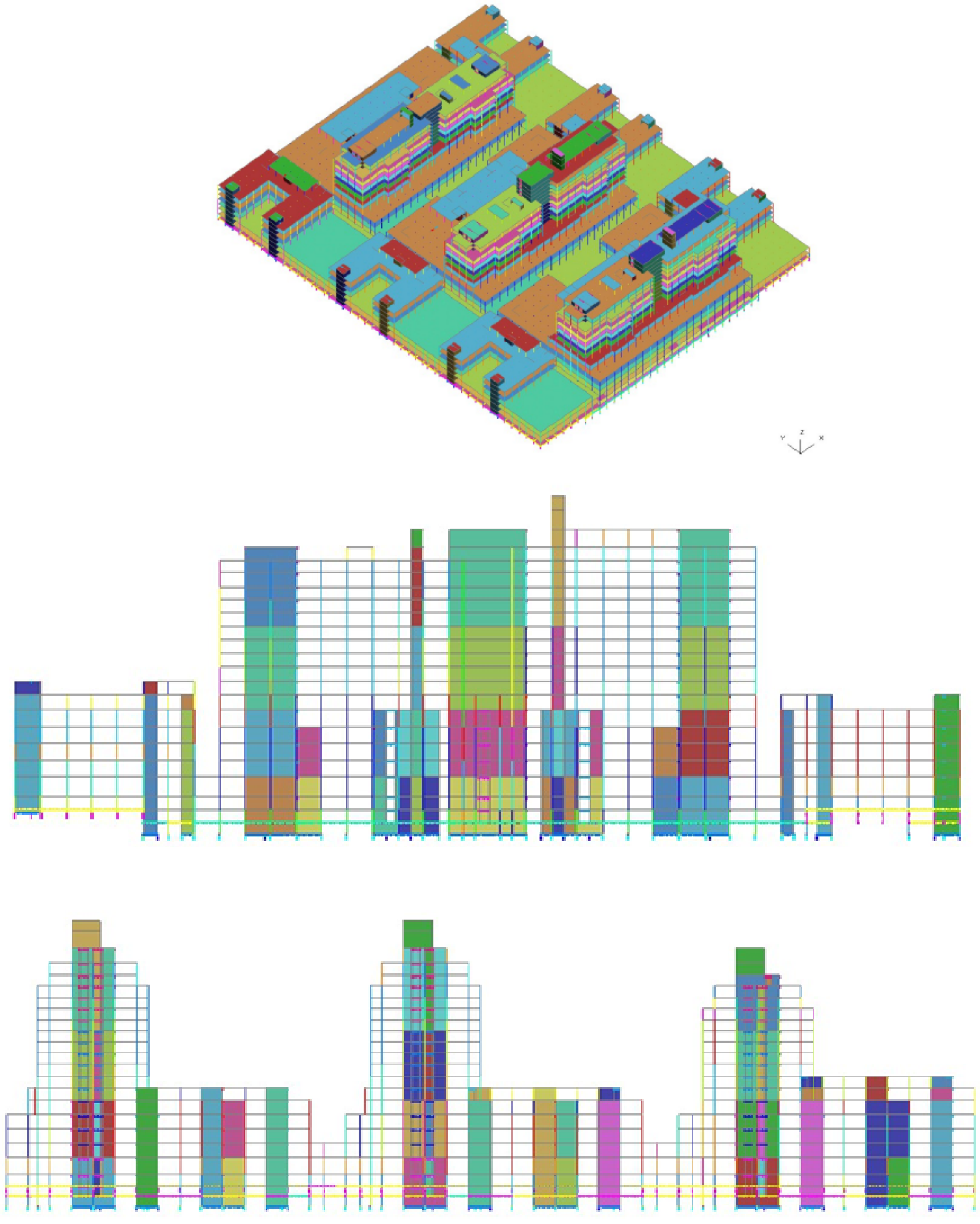
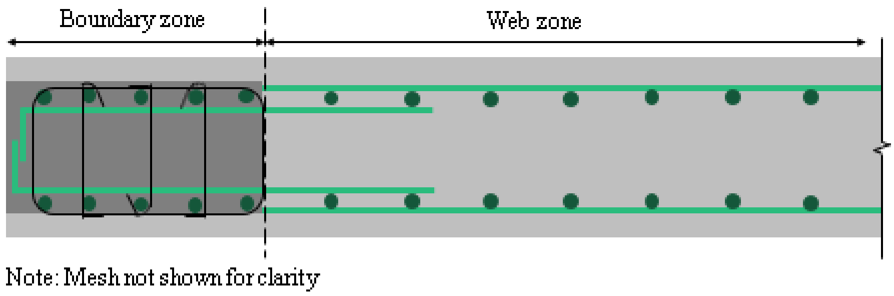


Fig. 7 – Nonlinear analysis model in LS-DYNA; isometric and elevation views

5.1. Core walls

Walls are modeled using layered shell elements, discretized to capture the nonlinear strain distribution along the length and height of the wall. MAT_Concrete_EC2 [4,5] is used as the material model for the walls. This material can represent a smeared combination of concrete and reinforcement. Wall shells are modeled with multiple through-thickness integration points that represent the concrete and reinforcement parts through the wall thickness (Fig. 8 – Layered shell model used for reinforced concrete walls The concrete model includes concrete cracking in tension, concrete crushing in compression, as well as reinforcement yielding, hardening, and failure. The compression behavior of the model uses the Mander algorithm (Mander 1992) [6]. MAT_HYSTERETIC_REINFORCEMENT [4,5] material is used to model the stress-strain behavior of the wall reinforcement, which captures reinforcement yielding, hardening, and strength degradation.

The use of finite element shells with MAT_CONCRETE_EC2 results in coupled shear-flexure interaction. Shear stiffness degradation of the core walls is explicitly captured in the model with cracking and compressive degradation in concrete.



Boundary zone	
1	Unconfined (cover) concrete
2	Vertical reinforcement
3	Horizontal reinforcement
4	Confined concrete
5	Confined concrete
6	Confined concrete
7	Horizontal reinforcement
8	Vertical reinforcement
9	Unconfined (cover) concrete

Web zone	
1	Unconfined (cover) concrete
2	Horizontal reinforcement
3	Vertical reinforcement
4	Unconfined concrete
5	Unconfined concrete
6	Unconfined concrete
7	Vertical reinforcement
8	Horizontal reinforcement
9	Unconfined (cover) concrete

Fig. 8 – Layered shell model used for **reinforced concrete** walls

5.2. Coupling beams

Hysteretic behavior of coupling beams is captured through use of a lumped plasticity model with the MAT_PARK_ANG_BEAM [5] material model. The elastic portion of the coupling beams are modeled with 0.2EIgross stiffness, and the plastic rotation parameters used are based on the ASCE 41-13 modeling parameters.

5.3. Isolators

The TFP isolators were modeled in LS-DYNA using the MAT_SEISMIC_ISOLATOR [5] material model. This model was developed by Arup, and throughout the project, additional features were added to capture all types of required isolators and relevant features to represent their behavior.

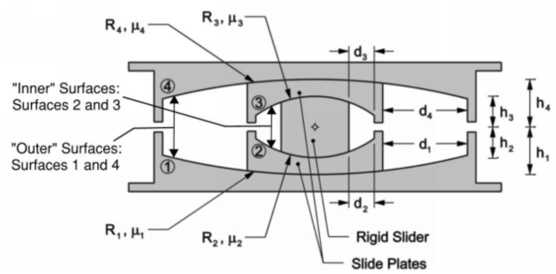


Fig. 9 – Triple Friction Pendulum schematic (adapted from Fenz, Constantinou 2007)

Triple Friction Pendulum isolators have a central puck and four low-friction curved sliding surfaces, shown in Fig. 9. In a standard configuration, the two outer sliding surfaces have larger matching radii of curvature (R_1, R_4) and the two inner surfaces have smaller matching radii of curvature (R_2, R_3). The two inner surfaces typically have the same friction coefficient (μ_2, μ_3), which is lower than those of the outer surfaces (μ_1, μ_4), which are typically different from one another. Together, the radius of curvature, friction coefficient, and displacement capacity (d_x) of each sliding surface dictates the behavior of the isolator. This behavior is shown below in Fig. 10.

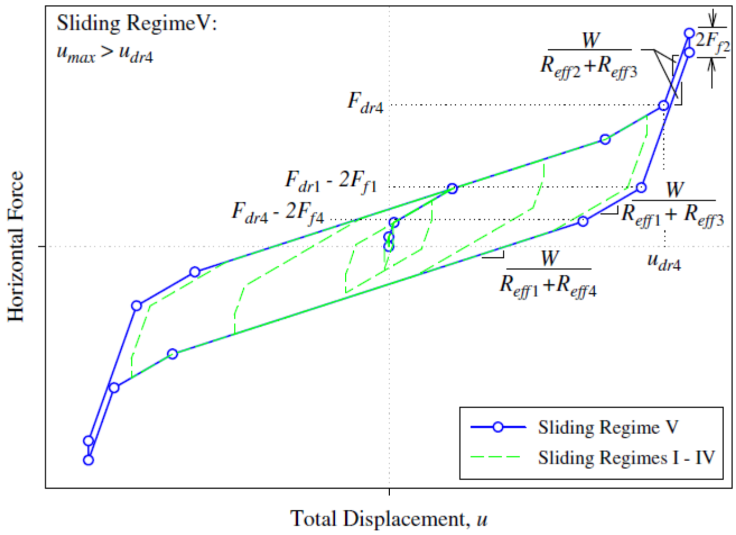


Fig. 10 – Hysteresis loop showing the full range of behavior of the TFP as it moves through all five of its sliding regimes (adapted from Fenz, Constantinou 2007)

In LS-DYNA, the TFP bearings were modeled using three beam elements in series with the MAT_SEISMIC_ISOLATOR material. The properties for these elements were calculated using the equations in the Fenz and Constantinou 2008 paper [7]. To further validate the behavior of the series model, key outputs were compared against those of a continuum TFP shell model (Fig. 11). The force and displacement results for uni- and bi-directional horizontal motion are shown in Fig. 12. For bi-direction motion, the continuum model calculates higher force demands due to imperfections in the sliding surface, but otherwise there is a good match between the two models.

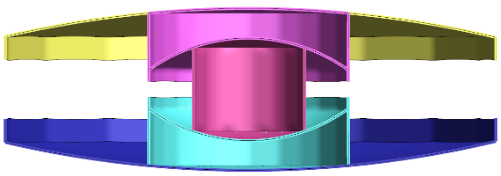


Fig. 11 – Continuum TFP shell model

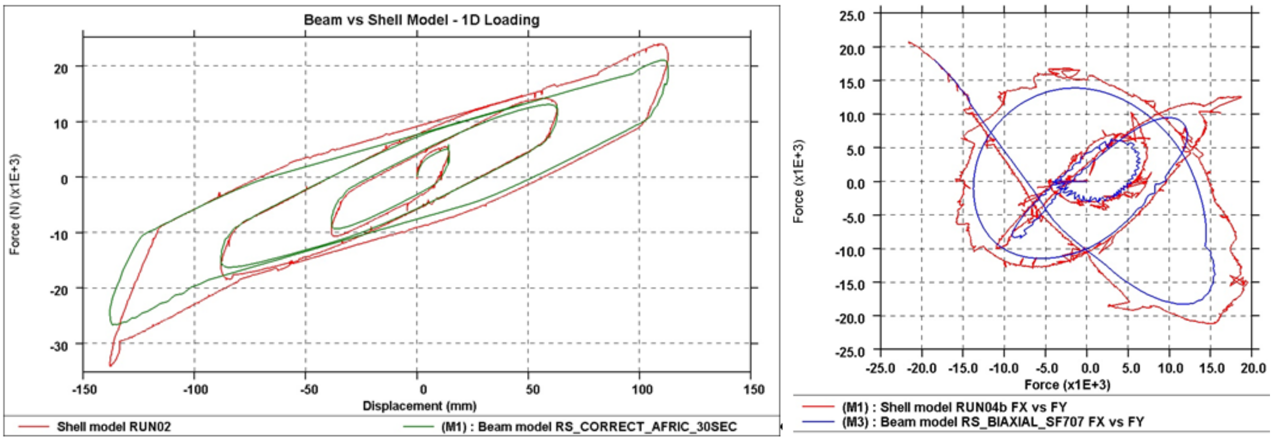


Fig. 12 – TFP lateral behavior results for continuum TFP shell model

6. Nonlinear Analysis

6.1. Cloud computing

Cloud computing was critical to the success of this project. A single analysis model itself was quite large with approximately 45,000 beams and 500,000 shell elements. To complete a full suite of analyses, 28 different models were run based on seven ground motion records which were rotated to 0 and 90 degrees, and with both lower and upper bound TFP isolator properties. Each suite of analyses resulted in approximately 4 TB of data. By running models in parallel on the cloud, it was possible to complete a full suite of analyses as well as run cloud-based post-processing scripts in about three days.

Once an analysis had finished on the cloud, a series of scripts would run to create csv files containing model geometry and both peak value and time history results. The scripts would then load that data to a database. This enabled the team to easily query the data and create standard reports that would summarize key results and identify any possible problems with each analysis.

6.2. Post-processing

With analysis results easily accessible on the database, the team could run a series of queries (using SQL) to extract various results. The database can hold basic outputs from LS-DYNA such as beam and shell forces and moments, node displacements and accelerations, and forces and moments at section cuts. Additional results requiring simple calculations were also stored on the database, as this is easy to do using SQL. Using custom components in Grasshopper, the team could connect to the database and request tabular data for whichever stored outputs were desired. These results could then be written to CSV files and plotted in a standard format using templates in Excel. For results where more complicated equations were required to calculate the structural parameter, or where desired plot formats went beyond Excel's limitations, Matlab scripts were written to do the calculations and produce custom-made plots (Fig. 13**Error! Reference source not found.**).

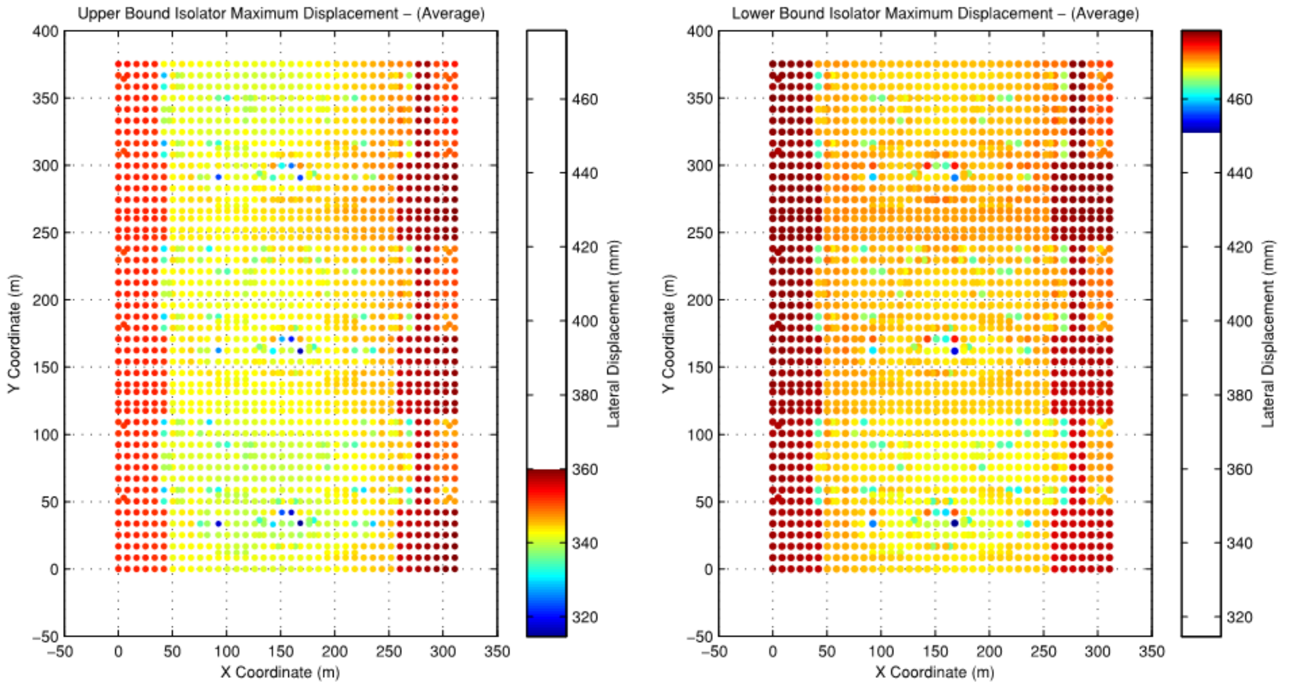


Fig. 13 – Sample analysis results showing upper and lower bound isolator maximum average lateral displacements

7. Isolator Selection

Before the final nonlinear analysis was performed, the full suite of analysis models were run with five different isolator type and layout combinations. Aside from the TFP isolators which were chosen in the final design, Lead Rubber Bearing (LRB) and High Damping Rubber (HDR) isolators were also studied. To create these models, the team used Grasshopper to quickly and parametrically add and remove isolator elements for each layout, along with their corresponding material properties. All isolator types were defined using the MAT_SEISMIC_ISOLATOR material model, which was able to capture and quantify key parameters for each isolator type, such as horizontal displacement, maximum compression loads, uplift for the TFP bearings, and tension demands for the LRB and HDR bearings. All the five different building models (superstructure and isolator type/layout) were subjected to the full suite of ground motions, resulting in a total of 140 nonlinear time history analyses. Performance-based evaluation results were presented in a report format for all the five different models. This enabled the client to select the optimal isolator type and layout for the project considering building performance, construction schedule, isolator cost and production speed. Table **3** provides some performance comparison of the three types of isolator schemes used.

Table 3. Performance comparison of different isolator schemes

Isolator type	Number of isolators	Base shear (E-W)		Base shear (N-S)		Isolator displacement (mm)	
		LB	UB	LB	UB	LB	UB
TFP	2068	8.5%	10.7%	8.4%	10.3%	478	360
LRB	2272	9.0%	15.0%	9.0%	15.0%	682	380
HDR	2773	11.5%	19.5%	11.1%	18.3%	519	193

8. Conclusions

Located in a high-seismic region in Istanbul, Ikitelli City Hospital was designed to satisfy ASCE 41 "Immediate occupancy" seismic performance objective under a very rare earthquake event. Supported on 2068 triple-friction-pendulum isolators, the hospital currently is the largest base isolated building in the world. To help the client select the most cost- and schedule-friendly isolator type for this large building, the design team conducted complete suite of nonlinear time history analyses using three different types of isolators and employed optimization methodologies to minimize construction costs and to improve floor plan efficiency. Conducting these studies within a tight project schedule for such a large-scale project required use of cloud computing and digital tools.

9. Acknowledgements

We would like acknowledge Prof. Mustafa Erdik's and Prof. Michael Constantinou's valuable feedback on the project. We would also like to thank our client, Ronesans Holding, for the collaborative work environment they provided, and Simon Rees (Arup) for his support. Special thanks go to Murat Melek for his valuable work and digital insight throughout the course of the project.

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