SEISMIC RETROFIT OF B'NAI ZION HOSPITAL USING AN INNOVATIVE DAMPED ROCKING-MASS SYSTEM

Y. Offir [(1)], Alex Shohat [(2)], A. Cohen [(3)]

[(1)] *Yaron Offir, Structural Engineer (M.Sc.), Yaron Offir Engineers LTD, yaron@yoe.co.il*
[(2)] *Alex Shohat, Structural Engineer (B.Sc.), Yaron Offir Engineers LTD, alex@yoe.co.il*
[(3)] *Abraham Cohen, Structural Engineer (M.Sc.), Yaron Offir Engineers LTD, avi@yoe.co.il*

Abstract

This paper presents the seismic retrofit design of the first major hospital to be retrofitted in Israel. This is the first out of four projects initiated and supported by the Israeli Ministry of Health, in accordance with a decision made by the Government of the State of Israel in 2010 to retrofit thousands of public buildings, assigning a $1,000,000,000 budget over a time period of 25 years.

B’nai Zion hospital was built in the 1950s-1960s in Haifa, which is situated near an active fault line, and is considered an area of high seismicity. The existing seven floor, 9,000 square meter Central Wing was originally constructed using “Debesh" walls, a unique Israeli building method, which was widely used in past decades. The concrete used in these walls contains very small amounts of cement paste, almost no steel reinforcement and is composed mainly of sand, stone aggregates, and impurities such as seashells. The seismic retrofit of the structure, which includes a 3,500 m^2 new extension, required detailed design and unique engineering solutions.

The existing structure was found to behave poorly during a seismic event. The predicted high seismic demands could not be accommodated in view of the low shear and bending capacities of "Debesh" walls. Hence severe damage was expected, mainly at low floor levels. The seismic demand imposed on various concrete elements reached an alarming ten times their capacity.

An efficient retrofit scheme, designed to prevent severe damage while avoiding extensive retrofit measures and thereby avoiding disruptions to ongoing hospital operations, was initially suggested. This included an innovative use of the new wing extension as a "Damped Rocking-Mass" system, by assembling 20 fluid viscous dampers at the gap between the existing and new structures. The limited horizontal displacements of the old concrete structure required developing the necessary velocities for efficient viscous damper action by taking advantage of the differential vertical displacements developed within the gap segments. In addition to the rocking base, a reversed toggle damper configuration was utilized to improve damper action at small relative velocities.

The project is in progress and requires a special coordination so as to ensure full operation of all hospital activities at all times. This can only be achieved with entire cooperation of hospital management and staff, to schedule the works and occupy areas as they are upgraded. This paper presents the parts of the project that have been already completed, including the unique toggle setup, which also enabled the creation of a critical passageway under the newly installed damper steel frames, and the installation of the “rocking foundations”. Several unique construction problems, related to the need of ensuring full ongoing operations at all times are discussed, as well as the solutions that were provided on-site.

Keywords: Seismic Retrofitting, Hospital Structures, Energy Dissipation Devices, Rocking foundation.

1. Introduction

A Syrian-African fault line running along the Jordan Valley on the Israeli Eastern Border is the main source of tectonic movement in Israel. The last reported strong earthquake of M6.3 occurred in 1927 [1] around the Dead Sea region and claimed hundreds of lives mainly from populated cities such as Jerusalem and Nablus. This event followed the earthquake of 1836 which claimed over 20,000 lives from the cities of Tzfat and Tiberias and some cities of southern Lebanon. It has been estimated that a major earthquake is expected every 80 to 100 years, meaning that most Israelis have never experienced such an earthquake in their homeland. This contributed to the lack of awareness about earthquake risks and hazards, until the 1999 Izmit & Kocaeli earthquakes which motivated the decision-makers in the Israeli government to create a dedicated governmental commission to tackle this issue.

Significant steps towards this aim began in 2005 with the seismic retrofit of industrial structures with hazardous materials and only in 2010 these efforts were extended to include various government agencies. The Israeli Government called to improve the seismic preparedness of the homeland establishing stages for the prevention, mitigation response and rehabilitation. The Health Ministry led these efforts with the objective to ensure that all hospital stuctures are complyant with current seimic codes, including retrofitting them where necesarry.

Four public hospitals were selected by the Health Ministry to initiate the seismic retrofit efforts. These hospitals are all located in high seismicity areas and were constructed before 1980, at a time when seismic loading wasn't included in design. The chosen structures are the Ziv Hospital in Tzfat, Poria Hospital near Tiberias, and Rambam and B'nai Zion in Haifa. This paper presents the design and implementation of the retrofit for the B'nai Zion Hospital which began in 2011 and was the first project to be executed.

2. Past seismic performance of healthcare facilities and the local Israeli code.

The 1994 Northridge earthquake served as a starting point for engineers to develop a new design approach to ensure not only structural integrity but also functionality after a major event. Even as the strength and stiffness of buildings were significantly increased after the 1971 San Fernando earthquake, during Northridge earthquake, several healthcare facilities remained unusable mainly due to nonstructural damage. Around 88% of all hospital beds in nearly intact structures required to be transferred from 13 medical facilities [2]. Severe damage was observed in medical equipment, fire suppression systems, piping and other nonstructural elements; there was crucial need for a new engineering knowledge to improve the design. The conventional approach was evidently inadequate, and hence a performance based approach was put forward. Performance Based Design, which clearly defines the acceptance criteria for both structural and nonstructural components for each performance level, is now widely used and is the leading choice for engineers.

The Israeli Standard SI 413 [3], the National Seismic Code for the Design of New Structures, was introduced in the late 70's and early 80's and has been updated over the years. However this code is not performance-based and is centered around a single life-safety performance objective under a design earthquake corresponding to a return period of 475 years or 10% probability of exceedance in 50 years. A separte standard for the seismic evaluation of existing structures, IS 2413 [4], is available but is intended only for a rapid evaluation rather than in-depth seismic performance assessment lacking the appropriate tools for retrofit.

The local code can be satisfactory, with some limitations, to the design of new structures but incomplete to assess and evaluate a retrofit design of this magnitude and importance as is the B'nai Zion Hospital. The design team, along with the Health Mnistry, decided to adopt international standards and opted to follow the guidelines of the Seismic Evaluation and Retrofit of Existing Buildings ASCE 41-06 [5], which, at the time, was the most recent and complete document addressing the performance based seismic design. This provided a set of evaluation and design criteria to ensure continued operation of the facility for the design return period, both structurally and nonstructurally. An immediate occupance criteria (IO) for a return period of 2475 years was selected as the design performance for the B'nai Zion Hopsital.

3. B’nai Zion Hospital - Structure

B'nai Zion Hospital, located in the City of Haifa- Israel, is government-owned and serves more than 200,000 patients yearly through its 450 hospital beds. The hospital’s total floor area is approximately 30,000 m^2 and is divided into three parts, each of which was built in a different period: The Eastern Building, built in the 1940’s; The Western Building, built during the 70’s and 80’s of the previous century; and the Central Building built during the 50’s and 60’s. The Central Building is the main focus of this paper.

The hospital, built on a slope of Mount Carmel (see Fig. 1), is considered to be located in a seismically active area, being only a few kilometers away from the Yagur fault. The Central Building is a seven-story tall rectangular structure, enclosing nearly 9,000 m^2 of built space. The main structural elements are "Debesh" walls made of low strength concrete characterized by a small amounts of cement paste, almost no steel reinforcement and impurities such as seashells. This brittle concrete was a popular construction material in past decades and can be found in many Israeli structures (Fig. 3). The structural system includes a concrete elevator and stair shafts, walls, columns and ribbed slabs, all supported on a shallow foundation.

As the original blueprints of the building were unavailable, the structure underwent extensive on-site measurements and structural testing, both destructive and nondestructive, to obtain essential parameters for evaluation. Valuable information regarding geometries, material properties, reinforcement details were thus collected and helped to reduce some of the uncertainties during the retrofit design process. The concrete was found to be of low strength, averaging 15 MPa in a 75 mm diameter cylinder core test, an approximate tensile strength of 1.1-:-1.6 MPa and no significant traces of carbonization were found. The steel, however, was found to be in good conditions.

Fig. 1 – Hospital compound aerial overview

4. Analysis of the existing condition

The earthquakes generated at two main faults contribute most significantly to the seismic hazard of design: a weaker M5.8 near fault (0-10km) ground motion generated by the adjacent Yagur fault and a stronger M7.5 motion produced by the African-Syrian fault located further away at a distance of 60-100 km. The disaggregation plot showed in Fig. 2 clearly shows that the nearby sources, up to 20 km are dominant and therefore govern for design.

Both linear and nonlinear analyses were performed for the Central Wing of the hospital, on two and three dimensional analytical models using the commercial finite element software packages LUSAS and SAP 2000. Material properties obtained from available information and test results were used. The foundation of the structure was modeled employing soil springs following the guidelines of ASCE 41-06 using upper and lower boundary values. Fundamental periods of 0.27 s long side and 0.47 s in perpendicular direction were determined from 3D model. Results obtained from the linear analyses showed the seismic behavior of Debesh walls to be very poor due to the lack of steel and reinforcement details, causing the already weak concrete to perform in a very brittle manner. Initial investigations highlighted that the structure is likely to suffer strong damage as a result of high seismic demands, with demand-capacity ratios (DCR) as high as 10 in various elements. Most of the damage was found to be concentrated in the lower levels.

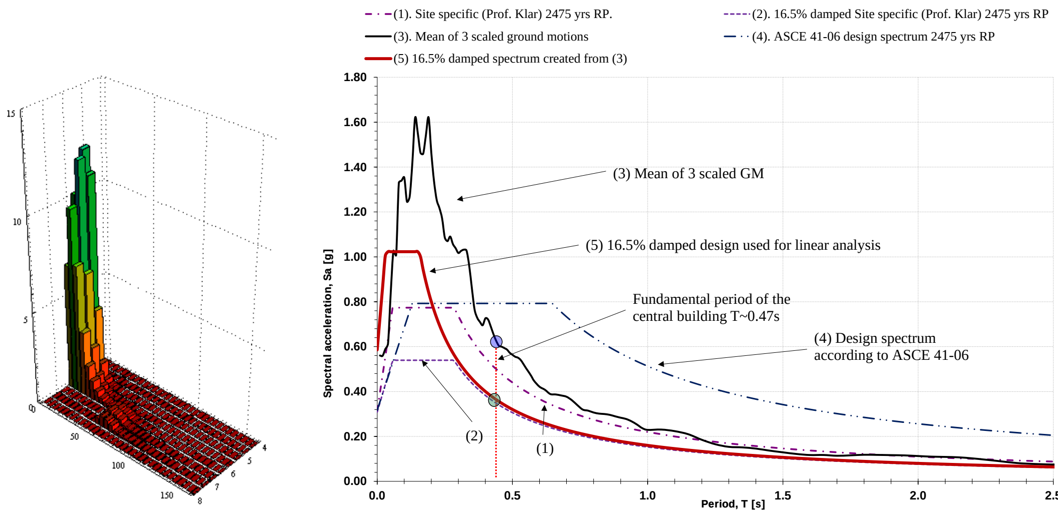

Fig. 2 - Disaggregation results obtained from site-specific survey for a period of 0.5s (left) and design spectra comparison (right) [1].

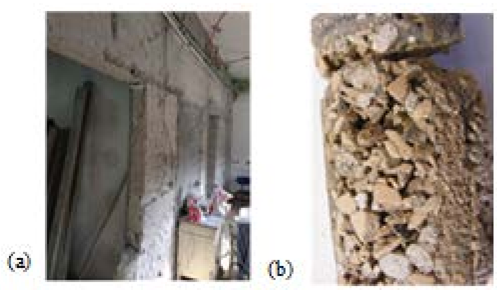

Fig. 3 - Exposed Debesh walls before retrofit (a) and an extracted Debesh concrete core for testing (b).

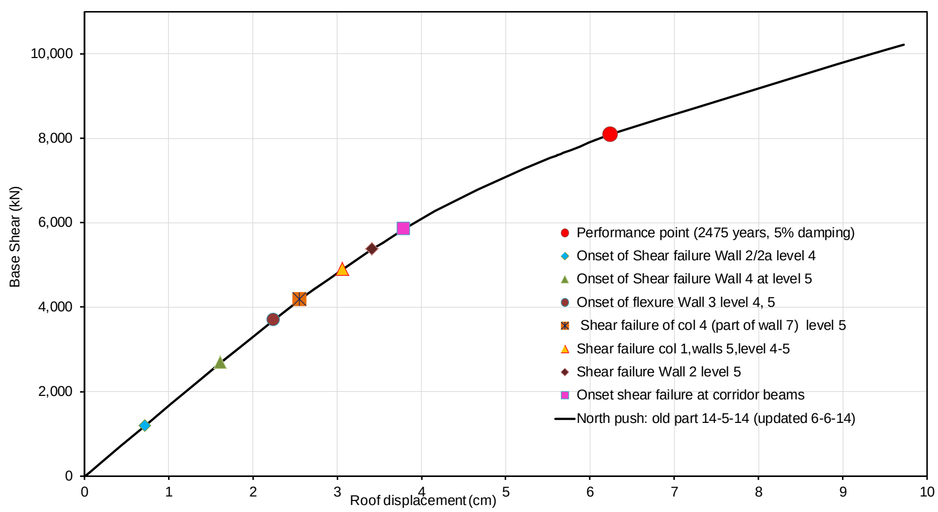

Fig. 4 – Pushover curves for the transverse direction of the existing central building structure showing the failure mechanism prior to the performance point (6.2cm).

Results from the pushover analyses performed using two dimensional models indicate that major yielding in important structural elements, mainly walls, is reached prior to the expected design performance point. Therefore, as shown in Fig. 4 the structure does not satisfy the target design criteria of immediate occupancy in a strong event.

The seismic assessment of the existing B'nai Zion Central Wing building, based on the results obtained from both linear and nonlinear analyses, revealed severe deficiencies in the structure's ability to withstand the expected seismic action. Most key structural elements in the building develop large DCR values showing their inability to cope with the earthquake demands. In addition, the building has torsional irregularity due to the eccentric location of the stair and elevator shaft. Finally, the small and even non-existing steel reinforcement contribute to the very low capacity of the main structural elements.

5. Retrofit design

As abovementioned, most of the Central Wing was built using Debesh walls, with little to no reinforcement, causing the structure to perform in a dangerously brittle manner under seismic loading. If the local seismic practice design was followed for the retrofit design, conventional retrofit measures such as strengthening and stiffening the structure would have been chosen, increasing the size concrete elements and adding new components. This would have required invasive measures that would have most likely interfered with the Hospital's ongoing operations. This clearly was not an acceptable option considering that a healthcare facility of this importance must continue to function at all times. The need to seek other retrofit solutions was eminent.

It was initially proposed to use a new extension that was planned for the Central Wing to alleviate the seismic demand on the original structure. This suggestion presented several technical difficulties which needed special attention. Because of geometric limitations, the lateral stiffness of the new extension could be only about a tenth of that of the existing stiffer walls. This, along with the already small inter-story drift levels, reduced the ability of the new walls to prevent damage to the existing elements. It was necessary to provide a passage to ensure uninterrupted flow of patients, staff and medical equipment, and this requirement limited the concrete element's cross sections. Lastly, an underground archive located under the new proposed extension, had a foundation which lacked the capacity to support the horizontal forces expected from the new structure. These limitations forced the design engineers to come up with innovative and elegant retrofit solutions.

6. Engineering solutions and its implementation

The chosen retrofit solution, which is schematically illustrated in Fig. 7, makes use of the initially proposed new extension to dissipate as much energy as possible during a seismic event. The use of energy dissipating devices located between the new and existing structures aims to significantly improve the dynamic performance of the existing structure. The connection of the new structure is such that the required intervention to the original wing is drastically minimized, including the reduction in the measures that would've been necessary to restrain nonstructural components. The use of viscous dampers in line with a rocking mechanism was the core of the retrofit design concept, as illustrated in Fig. 5.

The use of a rocking wall in parallel with supplemental damping has already been implemented in Japan [6]. This case, unlike the present one, incorporates friction dampers and the new and old structures are very close to each other. The case for the B'nai Zion retrofit presented additional obstacles that required careful attention, which are briefly mentioned.

- The small horizontal displacements and inter-story drifts of the stiff existing concrete walled existing structure were not able to develop sufficient relative velocity between the new and existing structures for the viscous dampers to work efficiently. A fixed support of the new structure would further reduce these relative floor displacements.
- The new extension could only be located at a distance of 4.6 meters form the existing wing due to site constraints and existing piping that could not be relocated. This relatively long passageway was designed in such a way that allows the engineers to take advantage of the amplified vertical displacements between the two structures in the damper configuration.

- The existing foundation of the Central Wing was robust enough and could easily accommodate the lateral reactions from its own upper structure as well as the loads generated from the new extension. As part of the design process, it was observed that if the foundation of the new building could be designed to resist the horizontal sliding forces, a rocking wall mechanism could be incorporated to further amplify the horizontal displacements, and thus, increase the efficiency of the viscous damper. The rocking wall foundation includes a shear key with a 70 mm horizontal separation gap (refer to Fig. 6) generated by neoprene pads preventing large shear forces from developing at the foundation level. This rocking mechanism significantly reduced the size of the foundation which would have required a large number of piles due to the existing underground archive.

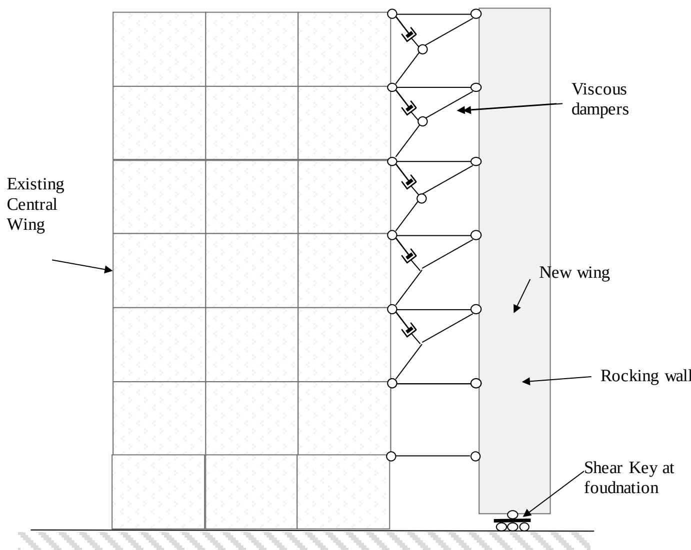

Fig. 5 – Retrofit concept using energy dissipating devices connected to a rocking wall

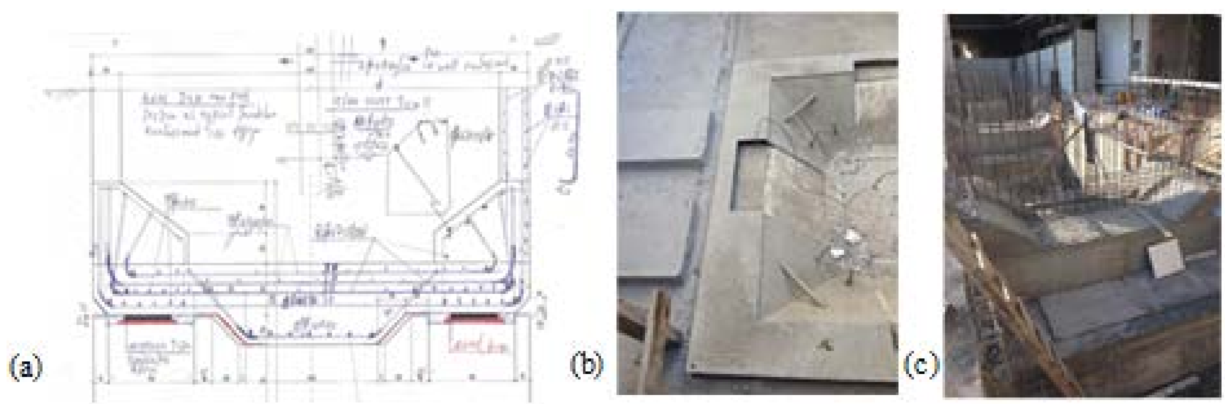

Fig. 6 – Construction of the shear key, part of the rocking wall foundation (a) sketch of the shear key and neoprene pads used to vertically support the rocking walls, (b) the steel plate used as a mold to provide the 70mm gap during casting (c).

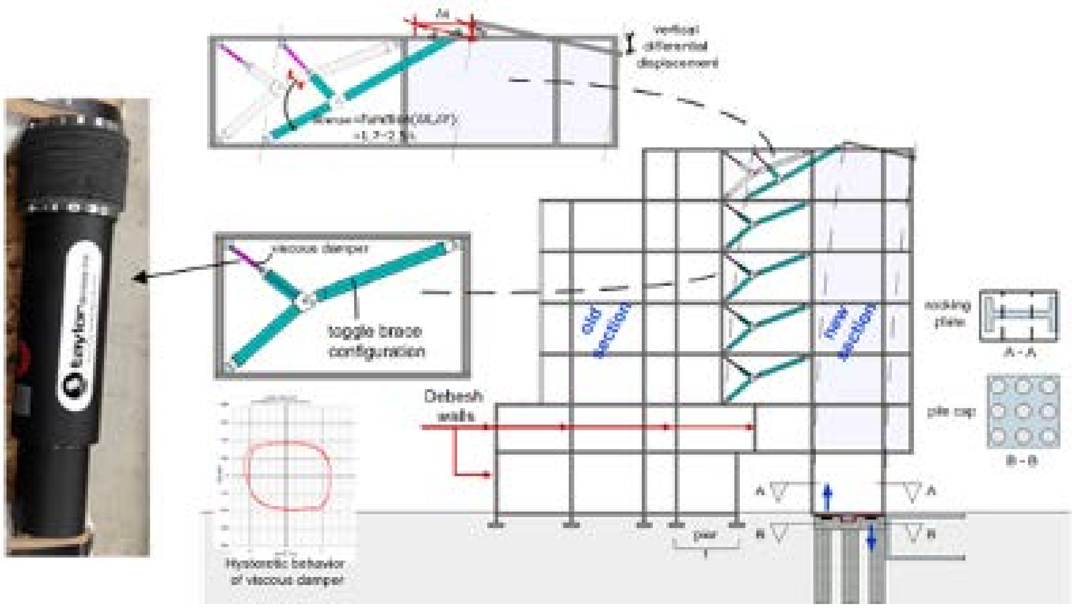

Fig. 7 - Final retrofit scheme. Connection of the viscous damper in toggle configuration between the existing and the new rocking structure. The hysteretic curve from the damper testing is shown (bottom-left corner).

6.1. Damper selection and optimization

In order to evaluate the dynamic behavior of the Central Wing and its new extension, a series of two dimensional analyses were performed. At a first stage, a nonlinear model was created representing the transverse section of the existing and new structures. The effective stiffness of the lateral resisting elements was calibrated to represent the whole building through displacements, equivalent stiffness and fundamental period.

Initially the dampers were selected through an approximate design according to Section 9.3 of ASCE 41-06, *Passive* Energy *Dissipation Systems*, where the damping coefficient C was obtained for each level. The dampers were distributed throughout the building placing four dampers per floor in line with existing concrete walls, connecting them to four out of six new *I* shaped concrete walls in the extension wing.

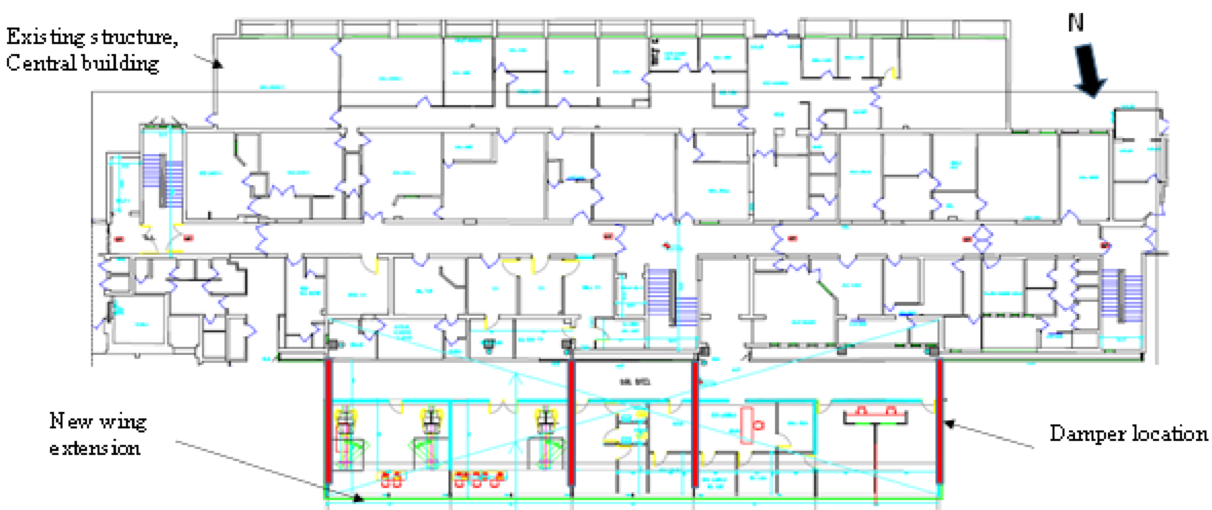

Fig. 8 - Damper floor layout

These dampers are spread through the top five of seven stories of the building. A total of 20 dampers is used. Because the bottom floor and the main floor hallway needed to remain clear, preliminary analyses indicated that a variation of the damping coefficient with the height yielded little benefits; therefore a single damping coefficient was selected for all 20 dampers.

Three scaled ground motions compatible with design spectrum were provided by the soil consultant: Landers 1992, Coyote Lake 1979 and Morgan Hill 1984, the latter being the most dominant at low periods (0.5s) which is similar to the fundamental period of the structure [1].

The viscous damping coefficient α, which is the exponent that relates the viscous damper force and velocity, was determined through a series of nonlinear analyses using diagonal configuration damper, varying 0.3, 0.5 0.7 and 1.0 as α values. A structure with no dampers was used for as a reference. Through the data from the analysis results it was possible to determine that the lower values of α yielded a better response. 150-200 tons dampers were sufficient to reduce the forces in the structure by 30-40% and the displacements almost by 60%. After few iterations, a final value of α=0.50 was selected, corresponding to a damping coefficient C of 3000. Analysis indicated that a shallow or deep foundation, required to withstand the design reactions of the new structure, would be impractical, and an innovative solution was necessary.

The selection of a reverse toggle configuration for the dampers was a result of a series of iterations during the analysis and design process with the supervision of Prof. Andre Reinhorn and Taylor devices, which was selected to supply the dampers. This new configuration allowed the design team to reduce to a third the damper forces, from 150 to 50 ton. The specific reverse toggle configuration fits all the geometrical constraints and provides a geometric amplification factor of 1.6 at the damper location. Moreover, this configuration allowed for the passageway of the connecting corridor to remain clear. A diagonal configuration resulted in a low efficiency of the damper and other more efficient configurations such as the upper toggle were rejected because of the corridor obstruction. Several other configurations were evaluated but eventually abandoned. The final damper configuration allowed the design team to reduce the size of the dampers, and thus resulted in significant economic savings.

6.2. Rocking foundation

The foundation of the new extension wing was designed as a pinned support, providing a vertical support while allowing lateral movement through a pile cap embedded shear key. The concrete block, comprising the massive foundation shear key, is horizontally separated from the pile cap by a 7 cm thick polystyrene sheet. This allows the structure to freely slide until the gap is closed and a locking mechanism is activated, which is needed to provide stability during a catastrophic event (see Fig. 6). On each of the four corners of the rocking foundation, a neoprene pad, designed following Eurocode standards [7], is installed to allow for the rocking mechanism to occur. By releasing the moment at the foundation level, the relative displacements between the old and new structures increased, thereby augmenting the efficiency of the damping devices. Detailed design was carried out to ensure the foundation will perform as expected, including a parametric study varying the soil properties. To ensure adequate implementation, special construction details were developed including supervision chambers where the neoprene pads can be replaced when required.

Time-history analyses were carried out with the foundation modeled using spring elements following Priestley and al [8]. Upper and lower boundary soil property values were employed to account for the uncertainty of the ground parameters. As anticipated, analysis results showed that the upper bound models yielded larger forces and smaller displacements, setting conservatively the forces for design. Only two momentarily uplifts s of approximately 1.0 cm during the motions were detected (see Fig. 9).

The elimination of the shear and moment reactions at the base resulted in increased axial forces at the floor connections, of up to 300 ton acting on one wall, as shown in Fig. 10. To counteract this demand, special reinforcement details were design to help distribute the load through the concrete slabs (see Fig. 11).

6.3. Torsional restraints

A special seismic detail was specifically developed to counteract the in-plane torsional effects of the existing Central Wing Building, caused by the asymmetry created by the location of the concrete pier. In order to further protect the Debesh walls from any additional shear stresses that are expected to be generated by the torsion, a pair of connection details was placed at the two expansion joints, separating the hospital wings (Fig.12). These details are composed from interconnecting steel plates that allow free movement in one direction while restraining any relative movement in the perpendicular direction. This detail allowed the three wings to move independently from one another in the longitudinal direction, where no torsional response is expected, while virtually cancelling the torsional effect. Fig.12 shows detailing and section cuts of the restraint.

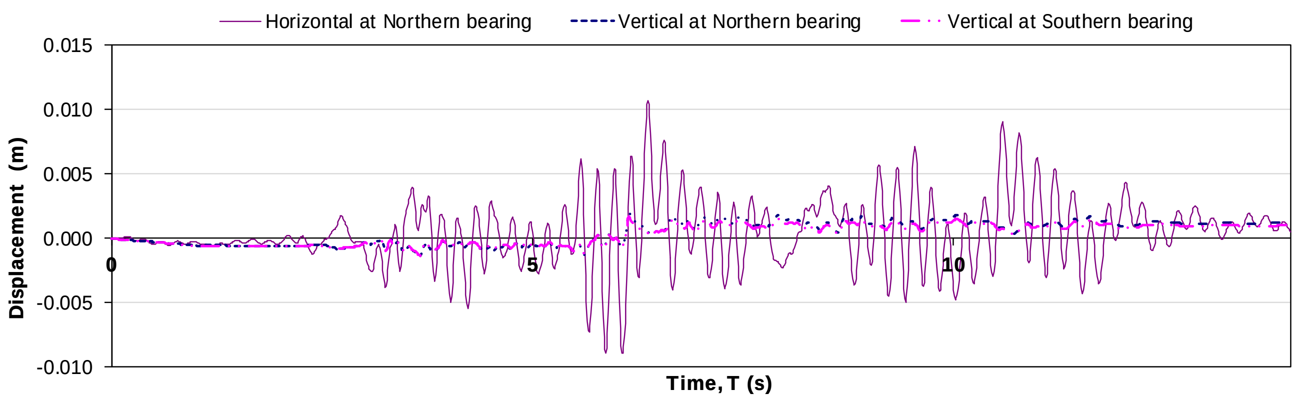

Fig. 9 – Vertical and horizontal relative bearing displacements, Morgan Hill 1984 ground motion using upper soil properties.

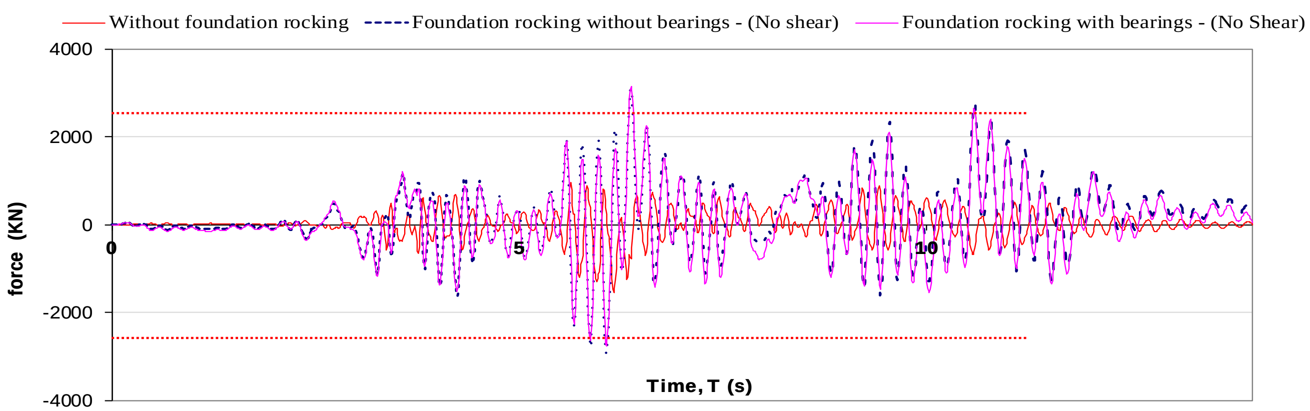

Fig. 10 - Floor loads at level 5 Morgan Hill 1984 ground motion using upper soil properties; damper parameters $\alpha = 0.5$ and $C = 3000$. Force comparison with and without rocking foundation.

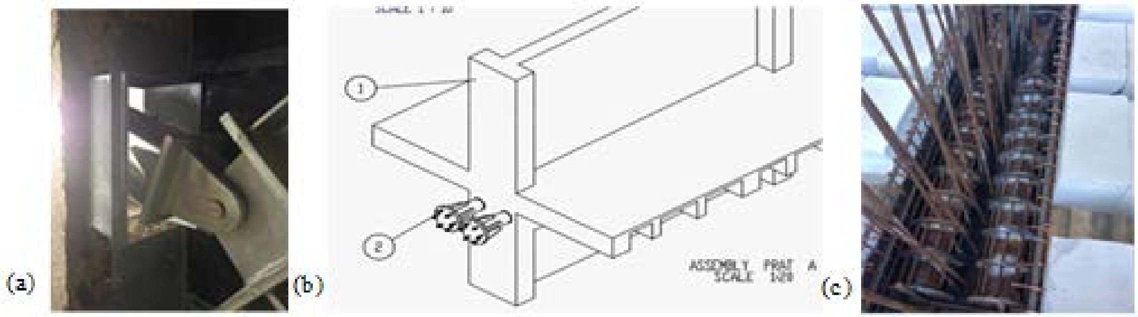

Fig. 11 – Reinforcement details: (a) Detail to prevent lateral buckling of the damper structure (b) assembly of anchor in the concrete slab to ensure stress distribution through the new slabs using twin schedule 80 steel pipe and (c) reinforcement before concrete casting.

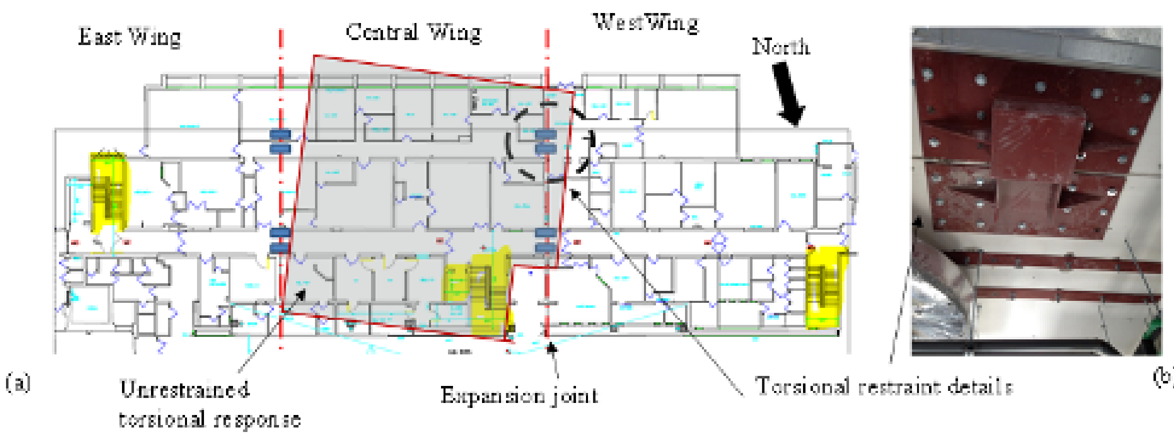

Fig. 12 - Torsional restraint detail and locations. (a) Typical floor layout and location of the restraints and (b) installed restraint.

6.4. FRP reinforcements

The failure mechanism of the existing Debesh concrete walls is shear-controlled, mainly due to the lack to transverse reinforcement in the elements. This virtually inexistent steel cause non-ductile behavior after cracking is initiated, leading to a dangerous, sudden drop in stiffness and strength of the concrete walls. In order to avoid this undesired phenomenon, the strength and ductility of the existing concrete walls was enhanced using externally bonded fiber carbon reinforced sheets, FRP and posttensioned thin steel plates. The FRP sheets increased the confinement of the element and increased its shear strength, thus resulting in a ductile response. The inclusion of longitudinal posttensioned steel plates increased the flexural capacity of the concrete walls. Fig. 13 shows images of design and site implementation.

Fig. 13 - FRP and steel plate concrete wall strengthening and its implementation on site

7. Conclusions

The retrofit design of the B’nai Zion Hospital is a result of extensive analyses and detailed design incorporating innovative engineering solutions in order to minimize the intervention on the existing structure. The rehabilitation works are currently ongoing without interrupting the everyday activities of the hospital. The success of this project is the result of using variety of retrofit engineering solutions, good cooperation with the Hospital staff and the responsiveness and support of the Israeli Health Ministry. Some of the main conclusions of the project are summarized below:

- Any planned extensions and renovations should be included in the design to take advantage of the new elements, the design of which is controlled by the engineer.
- Sequential planning of the retrofit works is essential, and must be coordinated with the renovation yearly schedule, so as to minimize the interference in the ongoing hospital operations.
- Retrofit using conventional means (such as concrete walls and heavy steel braces) inside operating departments is not a privileged option, due to the massive intervention required.
- The retrofit design should include rehabilitation of the facades and nonstructural systems.
- Laboratory and site material testing campaign should be carried out to reduce uncertainties in the design process, and thus increase the reliability of the analysis results.
- Seismic retrofit using advances technological solutions such as energy dissipation devices and rocking mechanisms requires detailed attention. A peer review carried out by a leading expert in the field is highly recommended.
- Due to the complexity of the works and construction, the design process must be carried out in coordination with hospital design teams.
- Hospital teams should manage the execution of the project, as they are the most familiar with the facility and its operations.
- Extended supervision of the designer during construction is required.
- Adequate restraints must be installed in vital nonstructural elements to ensure the design performance criteria of immediate occupancy.

The B'nai Zion Hospital retrofit project is unique in many ways, and has served as a flagship project for future rehabilitation projects in Israel. The project is currently under construction with little interference to the normal hospital operations.

8. Acknowledgments:

The retrofit project described herein was carried out under the issue of the Israeli Ministry of Health, and with dedicated support of Engineer Katia Kubrick - Ministry of Health -Senior Project Manager, Engineer Kalman Markovitz- Structural Engineer appointed by B'nai Zion Hospital, and Mr. Erez Shimko- Administration Manager of B'nai Zion Hospital.

The retrofit design was Peer Reviewed by Prof. Gian Michele Calvi, from Studio Calvi s.r.l. in Pavia, Italy; who was selected by the Israeli Health Ministry form an international tender. His input and comments were helpful to pin down analysis and design details [9].

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