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SEISMIC UPGRADE OF BC HOUSING'S 20 STOREY NICHOLSON TOWER IN VANCOUVER, CANADA

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SUMMARY

BC Housing manages an extensive inventory of subsidized housing mostly in the Vancouver area. They have undertaken a program to carry out seismic retrofitting of key aging facilities that have high tenant occupancy and have been determined to have a high risk of severe damage or collapse for the code specified earthquake. Design of seismic retrofitting of a permanently occupied residential tower is a challenge that must balance cost, maintain fire safety and minimize disruption to the tenants.

This paper presents the retrofit design of a 20 storey concrete tower in Vancouver's "West End", an area of dense high rise construction. The concrete shear wall structure was originally constructed in 1969 and houses some 250 tenants. The initial three-dimensional response spectra analysis, using both SAP2000 and ETABS software, determined the load distribution to the existing non-ductile structural components and the capability of the existing structural system to contribute to the final retrofit structural system.

The retrofit solution included the construction of external concrete shear walls up to the 17th floor, along with associated foundation requirements both external to the building and within the basement and strengthening of the buildings two internal stairwells using continuous steel plates. A key aspect of the retrofit was the continuous vertical sawcutting of the concrete core within the elevator shaft to modify the stiffness in a manner that best suited the overall structural response.

Making provision for adequate fire exiting during construction was key. This and other lessons learned during the construction period are also presented in this paper with conclusions regarding the effectiveness of the various aspects of the retrofit with respect to tenant disruption and constructability.

INTRODUCTION

Nicholson Tower is a twenty story concrete residential building with a one level underground basement. The building, located in downtown Vancouver, was designed in 1968.

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In 2001, Sandwell Engineering Inc. was retained by BC Housing to carry out a seismic evaluation and upgrade project for the facility.

A previous seismic evaluation report prepared by other consulting engineering firm indicated that:

The seismic resistance of the structure is approximately 20% of that required by the National Building Code of Canada (NBCC) 1985 in the East-West direction and 35 - 40% of code requirement in the North-South direction. A later report by the same firm in November 2000, indicated that there has been an increase of 2% to 7% increase in the design seismic forces in the current code (NBCC1995) and hence the previously calculated seismic resistance would be even less.

The scope of the seismic upgrade program developed by Sandwell is described below:

Evaluation of Structural and Non-structural components

- Review in detail existing drawings and previous reports.
- Carry out a site visit including the basement, main floor, typical upper floor, and roof/penthouse to confirm the construction and condition of the building. Non-structural elements were also be identified.
- Develop a simple yet complete 3D computer model incorporating all structural elements to assess the building behaviour.
- Carry out a seismic evaluation of the building.
- Assess the seismic capabilities of the non-structural elements.
- The work to follow the BC Seismic Mitigation Branch's Provincial Guidelines.
- Identify seismic deficiencies and rank them in order of severity.
- Develop mitigation concepts and an order of magnitude construction budget.
- Submit report to BC Housing.

Schematic Design and Design Development

- Expand the information developed in the evaluation phase to include additional details, and refine the analysis as required to optimize the preferred upgrade solution.
- Retain a Geotechnical consultant to assess soil-structure interaction and to obtain all the standard geotechnical parameters.
- Prepare upgrade schemes able to be carried out either as one contract or sequentially over a period of years.
- Update the construction budget estimate.

Consultant Services and Detail Design

- Meet with BC Housing to discuss any outstanding or new issues arisen.
- Retain the services of an architectural firm to select the most appropriate scheme and to develop the detail architectural drawings, including the fire exiting during construction. In addition, retain a mechanical and electrical consultant (in-house Sandwell staff used).
- Develop structural detail drawings following any BC Housing standard requirements.
- Include drawings with mitigation details for non-structural systems.
- With the work at 95% completion, update the cost estimate.

Construction Documents, Tender and Negotiations, Field Services

- Issue for tender the drawings and specifications.
- Provide tender assistance and recommend a contractor.
- Provide field services during construction, including site inspections.

BUILDING DESCRIPTION

General

- Number of stories above ground: 20
- Number of stories below ground: 1
- Main plan area: approximately 54 feet x 128 feet
- Floor to floor heights: 12 feet at ground floor, 8.5 feet at typical upper floors
- The soil conditions in this area are generally considered to be good.

Figure 1 Original Building General View

Reference Material

The evaluation was based on the following existing drawings:

- 1968 architectural drawings
- 1968 structural drawings
- 1968 mechanical drawings
- 1968 electrical drawings
- 1986 fire protection drawings
- 1986 piping renovation drawings
- 1987 garbage chute sprinkler drawings

Structural system

The structural system, as illustrated in Figure 2, is summarized below:

- 6” thick concrete slabs supported on concrete walls (which carry both gravity and lateral loads).
- Stairwell concrete walls are 8” thick throughout.
- Reinforced concrete shear walls 10” thick at ground and 12” at basement; majority of the other walls are 8” thick from 2nd floor to 9th floor, 6” thick above 9th floor.
- The concrete walls in North-South direction are well distributed along the length of the building.
- A stairwell at each end of the building and an elevator shaft are the only lateral load resisting elements in East-West direction
- Five of the shear walls in the N-S direction have a "soft story” at the ground floor due to door openings; similar openings exist in the basement.
- Walls are supported on narrow strip footings of unreinforced concrete (exterior walls) and of reinforced concrete (interior walls).
- 4” thick unreinforced slab on grade in basement.
- Top three floors have utilized semi-lightweight concrete.
- Reinforced concrete elevator penthouse.
- 6” thick, 3 feet high reinforced concrete parapets around the roof perimeter.

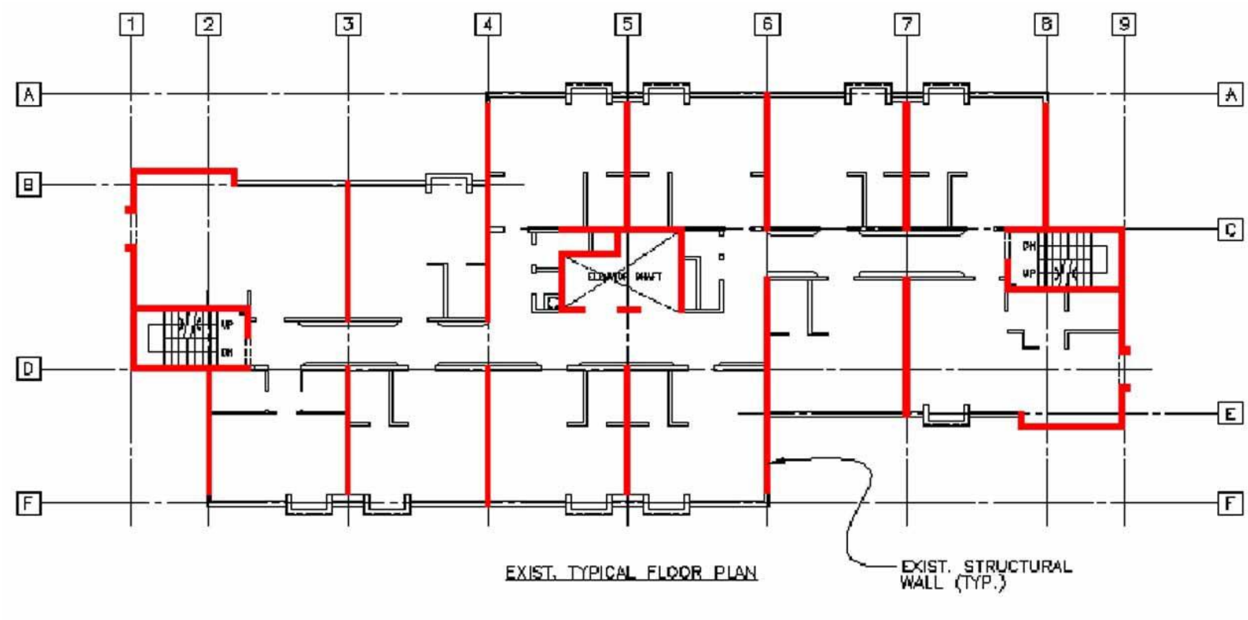

Figure 2

SEISMIC CRITERIA

Regional Seismicity

The West Coast of British Columbia, an area that includes the major portion of British Columbia's population has been determined by geoscientists to be susceptible to large earthquakes – in fact, the largest expected in Canada. There is evidence that several large earthquakes in the range of magnitude 7 have struck this area in the last 200 years. These include:

- A magnitude 7.2 earthquake located some 100 km southeast of Vancouver in 1872
- A magnitude 7.0 earthquake located off the West Coast of Vancouver Island in 1918
- A magnitude 7.3 earthquake located on Vancouver Island in 1946.
- Numerous smaller earthquakes.
- Evidence that larger earthquakes, perhaps greater than magnitude 8 have occurred.

Geoscientists suggest that the area is due for an earthquake of magnitude 8 or greater originating from the subduction zone off the West Coast of Vancouver Island, or a shallow crustal earthquake of magnitude 7. Past earthquakes have caused little damage because of the low populations in the affected areas at the time, and the preponderance of wood-frame houses. Today, however, with the area's large population and the great variety of building types, the evidence from recent earthquakes in California and Washington State clearly indicate that extensive damage can be expected to both structural and non-structural systems.

Reference Seismic Code

This paper refers to the seismic provisions outlined in the most recent edition of the British Columbia Building Code (1998 edition) which, for seismic issues is the same as the1995 Edition of the National Building Code of Canada (NBCC 1995).

Using this code, the base shear for a building, that is, the design force to be used in design is established as:

$V = V_e\ U / R$ (Design Seismic Base Shear)

Where:

$V_e = v\ S\ I\ F\ W$

R = Force modification factor that reflects the capability of a structure to dissipate earthquake energy through inelastic behaviour. This factor also recognises the existence of alternate load paths or redundancy in the critical structural elements, thus increasing a number of locations where energy can be dissipated and also reducing the risk of structural collapse as a result of failure in the individual elements. Values of R factor vary from 1.0 for non-ductile structures to 4.0 for well-detailed ductile steel or concrete structures. The current structure does not have structural elements with suitable proportions and details that can develop plastic hinges that absorb energy, therefore a value of R =1.5 was considered appropriate since there is a very limited redundancy and ductility capacity.

U = This is a calibration factor equal to 0.6, and it has a constant value for all types of structures.

v = This ratio is based on ground motion associated with a 10% probability of exceedance in 50 years (1/475 probability of annual exceedance). This is the probability used by most seismic codes to meet their performance definitions of life safety. For the Vancouver area, v = 0.2 (approximately equivalent to 0.2 g peak horizontal ground acceleration).

S = Seismic response factor, related to fundamental period of the structure. The fundamental periods in each direction were obtained dynamic analysis and the calculation of the S values was computed with these periods.

I = Importance factor. For ordinary buildings like the present, the factor used is 1.0.

F = Foundation factor related to soil conditions, varying in the range from 1.0 to 2.0. In this case, a factor of 1.0 suitable for good soil conditions was used based on the geotechnical report.

W = Weight of the building which creates inertial forces during an earthquake. It includes the dead load plus 25% of the Snow load on the roof.

Analysis Assumptions

The software ETABS was used for the computer analysis of the structure, with the following assumptions:

1. Floor slabs were assumed to act as rigid diaphragms within their plane for the evaluation phase. For the design phase cracked slabs were incorporated in the model to refine the analysis results.
2. For the evaluation phase, out of plane bending stiffness of slabs was not included, i.e., concrete shear walls were considered to be the sole lateral load-resisting system.
3. The ground level was assumed to be laterally supported by surrounding soil.
4. Fixed supports at foundation level for the evaluation phase. For the detailed design the soil stiffness coefficients were incorporated.
5. Effective stiffness ratios used in modeling the concrete elements (to allow for reduced stiffness due to cracking):
   - 0.7 for walls
   - 0.2 for beams and slabs

The assumption of lateral support at the ground level may result in unrealistic forces in elements below ground. Thus only the results for elements above ground were used from this analysis. In the detailed design, springs were included in the model representing the soil flexibility to refine the analysis results. A second series of analyses was performed considering no lateral support at the ground level (assuming that the small displacements at this level, of magnitude of less than 10mm, will mobilize only a small portion of the passive resistance of the soil at this level and may be neglected). This analysis did not govern the design of below ground elements.

In both analyses, it was assumed that the inertial forces from the weight of the ground floor will be directly resisted by the basement walls and soil.

SEISMIC EVALUATION OF THE ORIGINAL STRUCTURE

Figure 3 is a key plan correlating the numbers used in the report to identify the single or combined wall sections that behave as lateral load resisting elements. The capacity of the seismic resisting elements as a percentage of the code specified seismic demand is presented in this section to illustrate the location of the deficiencies and indicate the extent of upgrade required to bring the building to a life safety level. The information given in this section is related to the structure in its original state before the seismic upgrade.

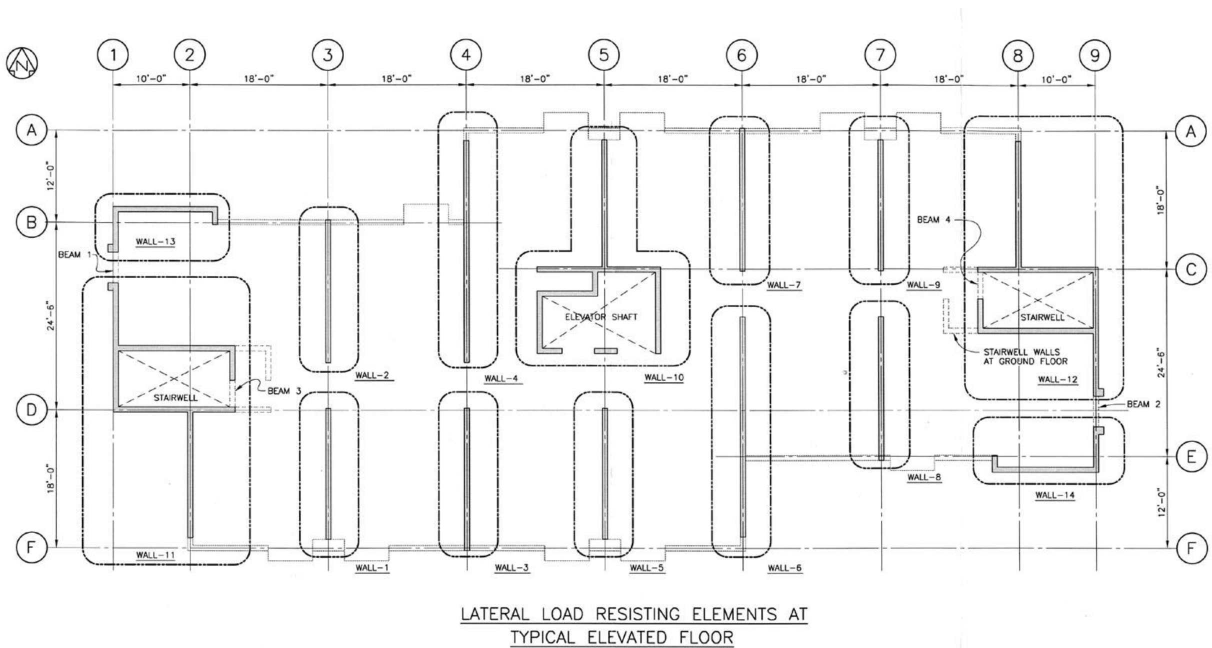

Figure 3

The "capacity to demand ratio" values in Table 1 primarily refer to axial forces and bending moments which are the governing failure modes in this structure. Those elements where shear forces are critical are specifically identified.

Table 1 Capacity / Demand Ratios

Element ID	Description	Capacity/ Demand Ratio
Walls 1, 2, 7,and 9		100%
Wall 3	L-3 and above Ground Floor Connection between ground floor and 2nd floor	100% 90% **60%**
Wall 4	L-3 and above L-2 Below L-2, South side of the opening Below L-2, North side of the opening	100% 85% **30%** **55%**
Walls 5 and 8	Connections of 8 inch walls at L-2 to the 14 inch walls below Elsewhere	75% 100%
Wall 6	L-3 and above L-2 Ground Floor	100% 85% **25~50%**
Wall 10	North - South direction East - West direction Shear in East-West direction	100% **~60%** ~75%
Wall 11 and 12	East-West direction North-South direction Shear Capacity	**~60%** **~25%** 70%
Wall 13 and 14	East - West direction North - South direction	**~30%** **~10%**
Beams 1 and 2	Connecting walls 11 to 13 and 12 to 14 Moment Shear	 **40%** **30%**
Beams 3 and 4	Headers in Stairwells	100%

Lateral drifts are within allowable limits of 2% of storey height:

Maximum inter-storey drift ratio in east-west direction: 0.8%
Maximum inter-storey drift ratio in north-south direction: 0.5%

Structural Deficiencies

1. Insufficient bending capacity of walls 11, 12, 13, & 14, beams 1 and 2.

These elements consist of large combined wall segments that are coupled by beams 1 and 2. These walls are stiffer than the other interior walls and as a result attract a major portion of the base shear. They also attract more torsional loading because of their location at the two extreme ends of the building. The combination creates large bending forces and axial forces (due to coupling) for which the walls and beams were apparently not originally designed.

2. Inadequate overturning (or up-lift) capacity at the footings of walls 10, 11, 12, 13, 14.
3. Lack of sufficient bending capacity in walls 10, 11, and 12 for loading in East-West direction.

4. High local stresses at points of vertical discontinuity such as:
    - Stairwell walls adjacent to door openings at level-2; due to significant discontinuity at one end.
    - Walls 3, 4, 5, 6 and 8 at ground floor (where openings exist)
5. Lack of sufficient shear reinforcing in the elevator shaft and the stairwell walls.
6. Strip footings were not designed for the high local bending at the locations of wall openings at basement.
7. The splice lengths of the vertical reinforcing steel were not adequate. The information on the drawings about rebar embedment lengths and lap splices was not complete and a materials testing firm was retained for mapping the current conditions of the splices.
   In the calculations the effect of the splice lengths was considered by using a reduction factor related to the ratio between existing and required splice lengths. A lap splice length of 20 bar diameters shown on typical column footing is not adequate to develop full capacity of the rebar according to current standards.

The calculations indicated that the soil bearing pressure under the walls at the two ends of the building (east and west ends) exceed the allowable limits. Bearing pressures under the interior walls were acceptable but some footings did not have adequate strength. Although the walls have significant bending capacity over their height, there was inadequate self weight and footing strength to resist bearing uplift at the base per the analysis; without adequate foundation restraint, these walls would be ineffective in the lateral load resisting system and hence transfer more load to the remaining walls.

The foundations of the two ends of the building were not designed for the relatively high overturning moments in the walls at these locations. Soil anchors are recommended at these locations to create base fixity and provide adequate overturning resistance.

STRUCTURAL SEISMIC UPGRADE

Guidelines

The following “guidelines” or targets regarding construction associated with the upgrade were used:

- Minimize work in occupied rooms
- Minimize loss of window area.
- Avoid disruption to common partition walls, to avoid costly and disruptive work.
- Stair Access to be maintained.
- Work during regular noise by-law hours.
- Noise and dust to be controlled as much as possible.
- Local rooms and areas can be vacated to allow work to proceed.
- Avoid relocation of piping and services.
- Work to be progressively implementable if at all possible.

Structural Upgrade

Figure 4 and 5 illustrate the basic concepts of this seismic upgrade.

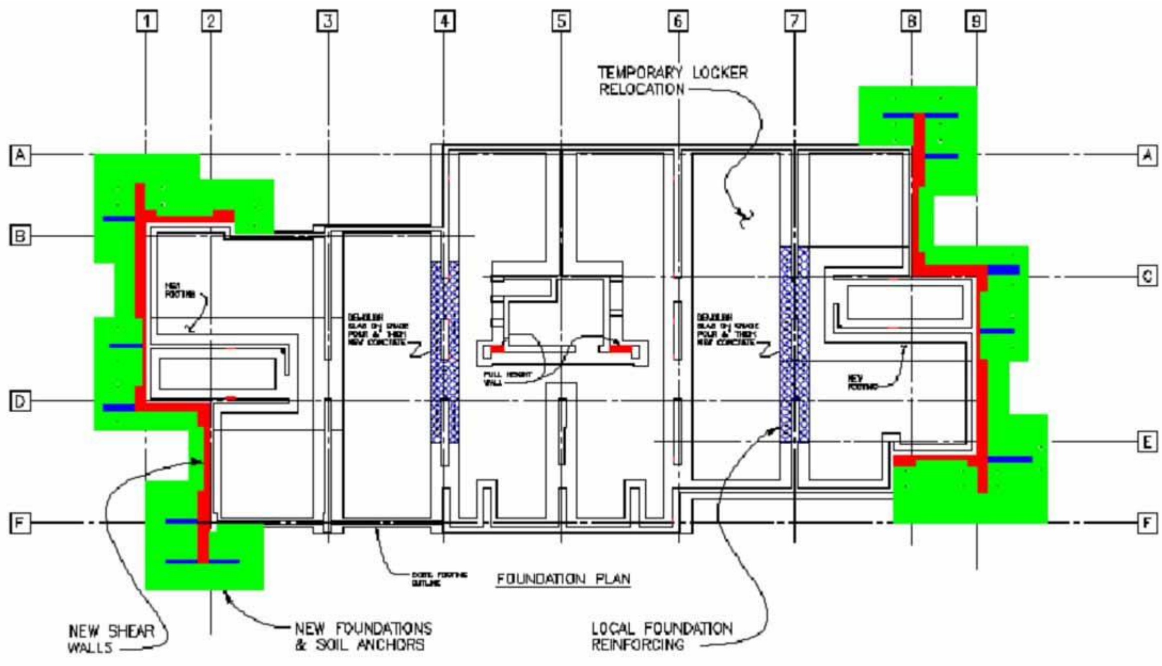

Figure 4

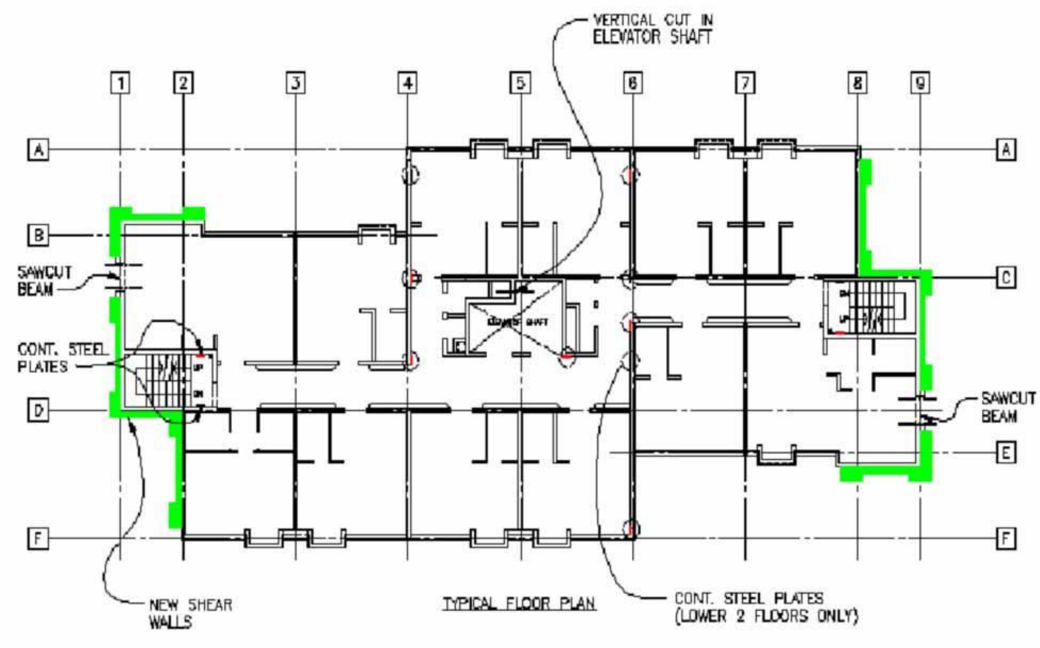

Figure 5

The seismic upgrade scheme to achieve a performance level consistent with 100% of NBCC 1995 seismic provisions includes:

1. Improve the foundation capacity by adding soil anchors at the four corners of the building (foundations of walls 11, 12, 13 &14) and the foundations of stairwells and elevator core (wall 10), to improve their base fixity to be consistent with the desired load path.
2. Increase the tension capacity of the connections of North-South walls at second floor to the walls below where openings exist (walls 3, 4, 5, 6 & 8).

3. Improve the bending capacity of the elevator shaft (wall 10) by adding steel plates dowelled into the existing walls (from foundation up to L-6).
4. Improve the tension capacity of the 4 ft long wall segments beside the stairwell door openings (in walls 11 and 12) using steel plates (from L-2 up to L-10).
5. Add transfer beams under the walls mentioned in item 4 at level-2, where the walls are discontinuous.
6. Isolate the 3 ft high up-stands under the window openings on (beams 1 and 2) from the adjacent walls to eliminate the coupling of the adjacent walls. This will:
   a. Increase the natural period of the building in North-South direction and consequently decrease the seismic loads in that direction.
   b. Prevent the high axial loads in the walls due to coupling.
1. Add a new reinforced concrete shear wall to the exterior of walls 11, 12, 13, 14 and dowel into existing walls at floor levels, from foundation to L-10. Foundation work will be required.
2. Retrofit of walls 11, 12, 13 &14 up to L-16.
3. Additional external steel plates at the ends of the walls 3, 4, 5, 6 & 8, from foundation to level-3, to enhance flexural capacity.
4. The walls of the elevator shaft were cut to reduce stiffness and therefore to reduce the forces acting on these walls to the level where upgrade to these walls was not required. The new external shear walls were designed to take the forces released from the elevator shaft.
5. Figures 6 and 7 illustrate the building with the additional walls attached to the existing walls. Figure 8 shows the original walls with the dowels required to transfer the seismic forces to the new shear walls.

Figure 6 Upgraded Building Overview as envisaged by the Architects

Figure 7 Upgraded Building Completed

Figure 8 Existing Walls and Dowels

Non-structural Systems
An inspection was carried out to review the seismic capabilities of the significant non-structural components within the building. They were reviewed both for life safety and for maintaining operations.

The following were noted:

Sprinkler Lines
The sprinkler system has recently been seismically restrained and is expected to meet the intent of the code.

Water And Steam Lines
These lines are supported within 12” of the ceiling and thus meet requirements.

Masonry Walls In Basement
These unreinforced masonry walls are approximately 8’ tall with a height to thickness ratio of 12. This falls within the range where upgrading is not required. The walls have a low vulnerability and a low consequence rating both for life safety and for function.

Electrical Panels – Ground Floor Electrical Room
These panels are mounted on high unreinforced masonry walls. It is expected that there could be damage to the walls and possible partial failure. They would have a low to moderate consequence rating relating to life safety and a high consequence rating relating to maintenance of function.

Mitigation includes the installation of vertical posts spaced approximately 4’ on centre spanning from the floor to the concrete ceiling. The masonry attached to the posts at 2’ on centre.

Gas Line
The gas line is located within 12” of the ceiling and meets the restraint requirements of the code.
It was suggested that consideration be given to the installation of a seismic shut off valve at the gas meter.

Emergency Generator
The natural gas fired generator appeared to be adequately anchored to the concrete slab. It was recommended that the battery pack be strapped either to the generator or to the floor.

Consideration was given to replacing the unit with a diesel unit that is independent of outside lifelines.

Boilers
Four spring-mounted boilers are located in the ground floor Boiler Room. The springs are not capable of restraining movement and there is a high probability that the boilers will move off the springs. The boilers have a high vulnerability rating. They have a low consequence rating for life safety but a high consequence rating relating to maintaining function.

It was suggested that snubbers be installed to restrict motion.

Boiler Room Piping
The piping is inadequately restrained and has a a low consequence rating for life safety and a moderate consequence rating for maintenance of function.

Horizontal Hot Water Tanks In Boiler Room
The tanks required additional restraint. They have a low to moderate vulnerability rating, and a low consequence rating for life safety and for maintenance of function.

Electrical Panels In Boiler Room
A number of electrical panels are attached to unreinforced masonry wall with similar vulnerability and consequences as discussed previously.

Glazing At Main Entrance
The glazing is made of tempered glass and should be a minimal hazard.

Brick Veneer over Main Entrance
Anchorage details of the brick to the backup walls are not known. However, veneer ties on buildings of this age have often been found to be significantly deficient. The veneer has a high vulnerability rating, a high consequence rating for life safety and low consequence rating relating to function.

It is expected that some damage would occur and some brick would fall. Most falling brick would be captured on the large concrete canopy over the main entrance. However, the canopy includes a continuous skylight at the side adjacent to the building. It is unlikely that the skylight could support the brick.

Three options were considered.

- Remove the skylight and replace by a more substantial material and in addition install parapets along the two sides to help restrain the brick from falling off the canopy.
- Pin the brick to a backup wall. A new back up wall would be required necessitating renovating within the suites for the full height of the building.
- Provide a decorative exterior brace connected to the brick and to the adjacent concrete.
- The second option was recommended.

Elevator
- Improve anchorage of guide-rails.

Fire exiting, disruption and learned lessons
Two emergency exits were located at the same locations as new shear walls. Initial consideration was to exit to the exterior through 2 temporary walkways spanning over footing excavations; however the contractor preferred diverting the egress routes into the main lobby for exiting. During construction a small fire occurred in the lunch area adjacent to the lobby, with the smoke from the fire filling both the lunch area and the lobby and entering one stairwell. The sprinkler system effectively put out the fire and no one was injured, however residents were concerned that they were unable to use one set of stairs due to the smoke. After this incident two separate emergency exits were created: one exit through the lobby and the other using a temporary walkway spanning over footing excavation. Although the temporary walkway created some inconvenience to the excavation, construction of the footings were completed without much impact. This illustrated the need to carefully assess the exiting requirements at the project, regardless of contractor preferences. The thick steel plates required to upgrade the interior walls of the stairwells are a good example of a lesson learned. The stairwell is a restricted space with limited access. The steel plates per storey height weight approximately 125kg each. The contractors had difficulties in lifting, aligning and bolting these plates to the wall. The design called for full penetration site butt welds for splicing of the plates; the weld test failed in all cases. Extra plates and strengthening fillet welds were added as remedial works. The use of a carbon fibre FRP system will be considered on future similar projects.

Some lessons learned from having major construction work on a residential building where tenants continue to live in the building during construction, were:

- Minimise disturbance to the life of the tenant, keep any work inside the building to a minimum. Avoid work on public areas that are frequently in use such as the entrance lobby and corridors.
- People become less tolerant to noise, dust and disruption when they feel their home was being "invaded". Although the construction noise level was below the City Bylaw limits and monitored by City officials, there were many complaints about noise and dust.
- The tenants were anxious to know what was happening around them; separating the tenant from the job site was a challenge. Site safety to the tenants is a prime concern; all tools and materials must be removed at the end of each day to leave the building clean and tidy.
- Flammable and toxic building materials should not be stored on site.
- Identify, if possible, hidden and buried building services. Damage and/or interruption of utilities like electricity, gas, cable and heat make very difficult the landlord/tenant relationship.
- Educating the tenants regarding the project before construction is a very important issue. All tenants should be aware of the type and extent of disruption to their daily life during construction. The purpose of the education should make the tenants realize that the benefit of getting a safer place to live, worth the short term difficulties and their extended patience.

The project was completed successfully, with the tenants ultimately hosting the landlord, consultant and contract to express their gratitude for reducing the life safety risk of their primary residence.

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