Progressive Collapse analysis of a heritage building using Applied Element Method –Hotel St George, Wellington

I. Prionas & M. Seifi

Harrison Grierson Consultants Ltd

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ABSTRACT: The paper describes the complexity of the seismic assessment and rehabilitation of Hotel St George in Wellington, a 1920's heritage, 8-storey concrete encased steel frame structure (c.10.000m^2).

The assessment was performed using Progressive Collapse Analysis. This method has been materialised into explicit requirements for redundancy in building codes.

Conventionally, the engineering industry uses a simplistic procedure for most seismic assessments, which models only linear beam and column elements. This neglects the contribution of walls and slabs, leading to uneconomic solutions. Walls and slabs may be considered secondary members in other types of analysis but in progressive collapse analysis, walls and slabs often behave as primary members with slabs carrying load though membrane action and walls providing alternate load paths in case of loss or extensive damage of columns.

The building has been modelled using the "Applied Element Method" (AEM). This approach allows tracking of the structural collapse behaviour passing through all stages of the application of loads including elastic stage, crack initiation and propagation in tension-weak materials, steel yielding, element separation and element collision. A significant breakthrough not only for the New Zealand industry but also for the international engineering community.

Extensive research was undertaken to overcome the modelling complexities to incorporate the riveted connections, slabs, infill panels, foundation and surrounding soil and to assess the performance of the structure using state of the art methodology.

A set of Numerical Integration Time History (NITH) analyses in compliance with AS/NZS 1170.5 recommendations was completed for the Progressive Collapse methodology. Various geotechnical and material testing was undertaken to confirm the parameters used in the analyses.

To validate the accuracy of the model, the results were checked against ASCE41-06 acceptance criteria in conjunction with AS/NZ code requirements and limitations.

The results indicate the efficiency of the specific methodology to visualise the extent, magnitude and direction of any potential collapse or crack occurrences within the structure and provide accurate insights on the performance of the building, leading to the most effective strengthening strategy.

1 INTRODUCTION

Harrison Grierson Consultants Limited (HG) were engaged by Primeproperty Group Limited to undertake a Detailed Seismic Assessment (DSA) for the Hotel St. George building located at 124 Willis Street, Wellington and provide the most effective strengthening scheme to upgrade the building to at least 70% New Building Standard (NBS).

The assessment was based on extensive site investigations. Progressive Collapse Analysis with NITH was used as the most suitable, sophisticated and state of the art analytical technique.

Our aim was to identify the critical structural weaknesses of the existing structure in order to develop a strengthening scheme that added strength and resilience whilst utilising the existing inherent capacity of the building.

2 BUILDING DESCRIPTION

2.1 General

The Building at 124 Willis St, Wellington, is a 7-storey concrete encased steel frame structure constructed in 1929-1930 (Figure 1) with an irregular L-shape configuration. It was designated for retail use on the ground floor and hotel accommodation for the upper storeys.

It is currently listed as a Class II heritage building by the New Zealand Historic Places Trust. Partial seismic strengthening of the building by addition of concrete shear walls in different locations of the building was undertaken in 2006.

The facade of the building consists of reinforced concrete infill panels with thickness of 230mm for the first 3 storeys and 150mm for the upper levels. It is penetrated by numerous window openings.

Figure 1. Aerial View of the building.

The gravity and lateral load resisting system comprises of the following:

- 200mm thick ribbed slabs act as diaphragms.
- Rolled Steel Joist (RSJ) beam sections encased in concrete.
- RSJ column sections encased in concrete.
- Shallow square RC pad foundations.
- The added (2006) RC shear walls.
- Tension rock-anchors under the added shear walls (2006).

The earlier strengthening scheme which involved adding 8 RC shear walls to the building was only partially completed. Walls 2 and 7 are the only walls extended full height while wall 3 terminates after level 1, and walls 1, 4, 5, 6 and 8 are built up to level 4 (Fig. 2).

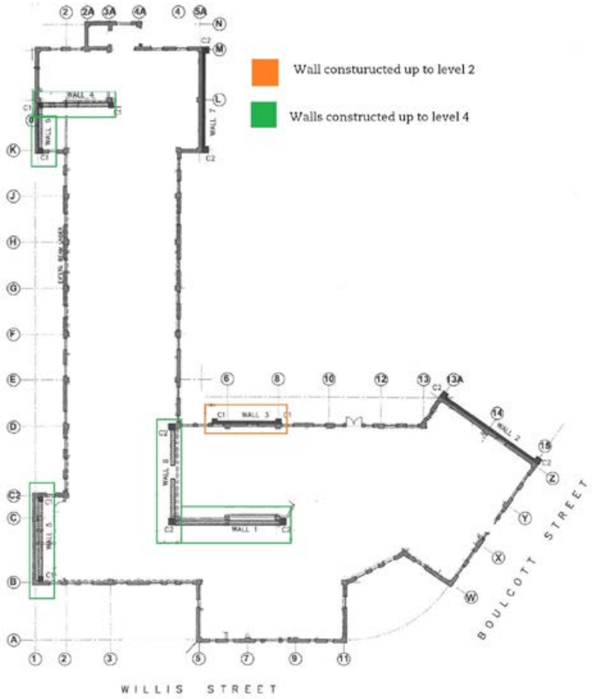


Figure 2. Typical Plan of Partial Seismic Strengthening.

2.2 Material Properties

The existing drawings for the building were obtained from the council archives. Given the age of the building these provided reasonable detail. However, there were areas of the drawings which were unclear (poor copies, etc) and some assumptions had to be made during the initial stages. There was also as-built information missing which was required for the detailed analysis we were to undertake. This information was probably not included in the original design documents of the time. This information was therefore obtained by laboratory testing of extracted samples of the building materials.

The testing schedule included compressive tests of the concrete cores using both crushing and Schmidt hammer tests, reinforcing sonar scanning, steel tensile, chemical and hardness tests, and concrete carbonation testing.

2.3 Geotechnical Conditions

The site straddles the site class boundary B-C, with the western portion of the building located on competent completely weathered greywacke. The profile dips steeply to the east/northeast towards the water front with the depth to completely weathered approximately 15m below ground level at the corner of Willis and Boulcott Street. Above the completely weathered greywacke is highly variable alluvial material ranging from very stiff silts to loose gravel deposits. Although the liquefaction risk over all is low some isolated pockets of susceptible material are present. The current high risk item from a geotechnical perspective is the low ultimate bearing capacity in some locations and the lack of as-built information for the foundations. Anecdotal evidence suggest that ‘soft’ material was identified during construction and that foundation excavations were extended through this material to ‘firmer’ ground.

3 INITIAL ASSESSMENT – ANALYSES PROCEDURE

3.1 Progressive collapse analysis

Progressive collapse (aka: Disproportionate Collapse) occurs when a local failure spreads throughout a structure from element to element, eventually resulting in the collapse of either the entire structure or a disproportionately large part of it. Progressive collapse is caused by an abnormal or extreme loading event, typically due to earthquake, accidental impact, faulty construction, foundational failure, or violent changes in air pressure (i.e. Blast). Infamous examples of progressive collapse can be seen in such history events as the terrorist attacks on the A.P. Murrah Building (Figure 3) and the Twin Towers of the World Trade Centre on September 11, 2001 or the Roman Point building (1968).

Figure 3. AP Murrah Building Progressive Collapse.

Utilizing the Extreme Loading® for Structures (ELS), HG has the ability to accurately analyse the behaviour of structures under extreme loads and to assess the risk of progressive collapse. ELS uses the Applied Element Method (AEM) to track and analyse structural behaviour from its elastic stage through cracking, element separation and collision. This method was used for modelling the building.

Progressive collapse and its dynamic effects may be evaluated using time-history analysis. Therefore, Numerical Integration Time-History (NITH) in accordance with AS/NZS 1170.5:2004 was used for the analyses.

3.2 Applied Element Method

In the AEM, the structure is modelled as an assembly of small elements made by dividing the structure virtually (Figure 4 (a)). Adjacent elements are connected by a set of one normal and two shear springs located at contact points, representing the material behaviour. These nonlinear springs are representing stresses and deformations of a certain volume (Figure 4(b)).

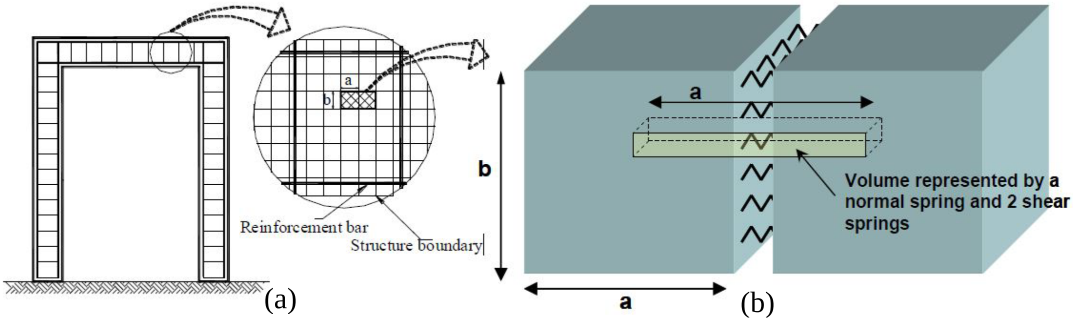


Figure 4. (a) Element Generation for AEM, (b) Spring Distribution and Area of Influence of springs.

When the average strain value at the element face reaches the separation strain , all springs at this face are removed and adjacent elements can be separated and they collide (Figure 5).

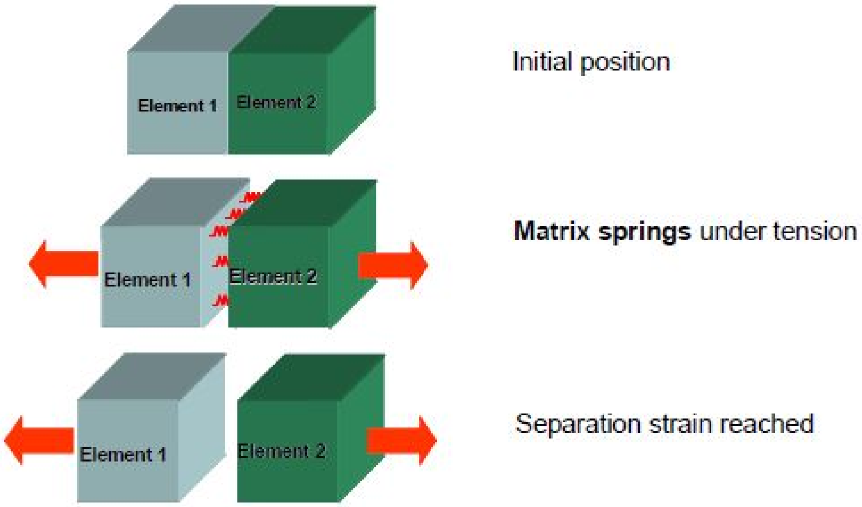


Figure 5. Element Separation.

The AEM is a stiffness-based method, in which an overall stiffness matrix is formulated and the equilibrium equations including each of stiffness, mass and damping matrices are nonlinearly solved for the structural deformations (displacements and rotations)

3.3 Extreme Loading for Structures (ELS) Software

ELS is an analysis tool developed by Applied Science International, LLC, based on the AEM method. It can perform nonlinear dynamic analyses for reinforced concrete, steel and composite structures. Modelling the building in ELS allowed us to monitor:

- Elastic to plastic deformation calculation
- Plastic hinge formation
- Buckling and post-buckling under compressive loads
- P-Delta effect and large displacement consideration
- Crack propagation and separation of elements
- Collision and collapse of separated elements.

3.4 Selection and application of ground motion records

Earthquake ground motion records used for time-history analysis are selected based on the recommendations of AS/NZS 1170.5:2004 and the research carried out by collaboration of University of Auckland and GNS Science.

The two horizontal components of the ground motions were appropriately scaled (factors k1, k2) and used for the analyses. As the structure does not have significant horizontal cantilevers or very long span beams the vertical components of the ground motions were not considered.

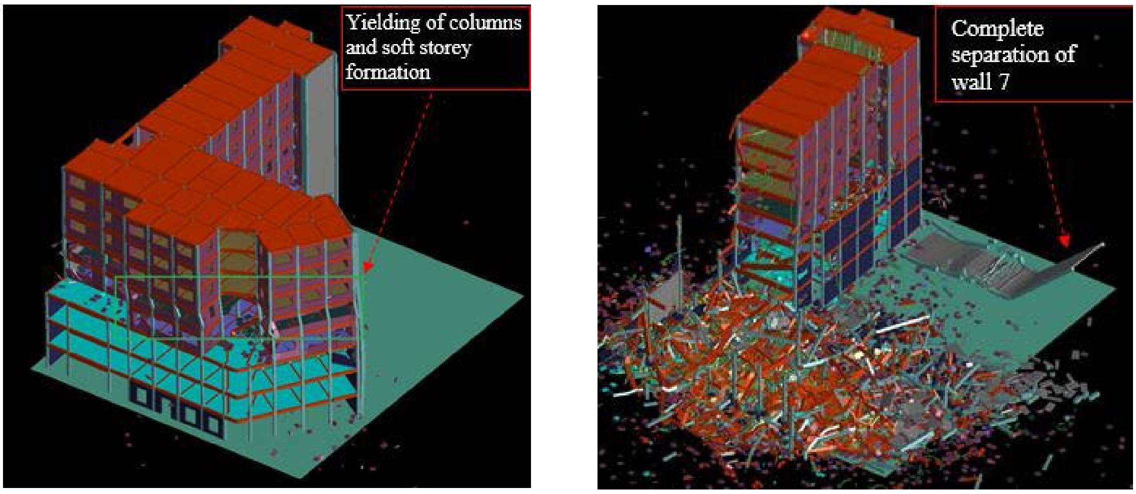
The particular of four ground motions used for analyses are as follows (Table 1):

Table 1. Ground motions used for analyses

Zone	Record Name	Date	M (MW)	D (kM)	Fault Mechanism	Forward Directivity	Applicable Type of Soil
North NF	El Centro	19-May-40	7	6	Strike-Slip	No	C and D
North NF	Duzce	12-Nov-99	7.1	8	Oblique	No	C and D
North NF	Tabas	16-Sep-78	7.4	2	Reverse	Yes	C
North NF	La Union	19-Sep-85	8.1	16	Sub. interface	No	C

4 ANALYSIS RESULTS OF EXISTING STRUCTURE

Upon completion of analyses of the existing building subjected to 100% of the selected ground motions it was found that the existence of critical structural weaknesses such as plan irregularity and vertical stiffness irregularity led to global or significant partial collapse of the building (Figs. 6 and 7).



(a) (b)

Figure 6. (a) Formation of Soft Storey Mechanism (b) Global Collapse-100% Duzce Ground Motion.

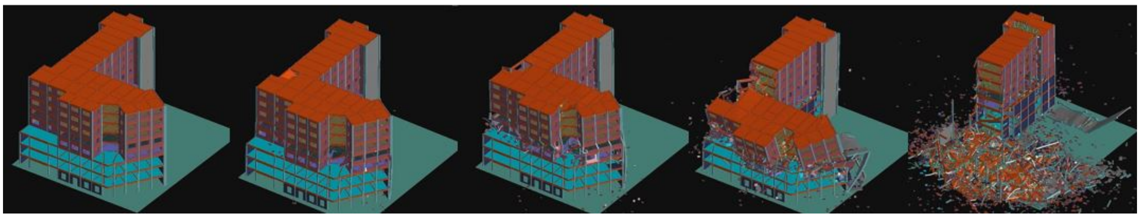


Figure 7. Sequence of the Existing Building Collapse Subjected to 100% Duzce Ground Motion.

The next step of our investigation was to determine the building's rating with respect to the New Building Standard (NBS%). Therefore the building was subjected to a certain percentage of the scaled ground motions and the performance of the building reviewed. The procedure was completed in an iterative process to determine a performance level in which the building performed satisfactorily.

A Detailed Seismic Assessment of the building in accordance with NZSEE and ASCE41-06 performance criteria was then carried out to validate the results of the progressive collapse analysis. The comparison between the analyses demands and the flexural and shear capacities of beams, columns and shear walls, verified that the software predicted capacities up to member's collapse stage (member separation) with high levels of accuracy and are in compliance with the codes performance criteria.

The results indicated that the building can achieve a seismic rating of 45%NBS. Our analysis was verified by an independent peer reviewer, an international expert familiar with the AEM method and the software used.

5 STRENGTHENING SCHEME

Following the analyses of the existing structure it was crucial to develop a strengthening scheme that would address the soft storey mechanism as well as the diaphragm's deficiencies.

This required the consideration of the client's requirements (maximise leasable area whilst creating a strengthened structure) and the wider communities and local authorities interests in the heritage aspects of the area (minimise any changes to the exterior of the building fabric).

Exploring several different options for the seismic strengthening of the building resulted with the continuation of the existing RC shear walls up to the 8th floor as the most effective solution. A comprehensive set of progressive collapse analyses using NITH method and the records mentioned in Table 1 were performed.

Interpretation of the attained results, showed that:

- Where the building was subjected to shallow crustal earthquakes without pronounced forward directivity features it experiences higher extent of damage.
- The extent of damage to the building subjected to 70% of the Duzce ground motion with the main component in the X direction is the most adverse.
- Extending the walls to the roof level, resulted in a better distribution of lateral loads among the resisting elements. The flexural failure of walls as well as flexural and shear failure of the beams as the main limiting factors of the building rating was resolved. Also, this measure has mitigated the soft storey mechanism as well as the detachment of the existing shear walls (2006) from the building.

Despite the strengthening scheme mentioned above, we observed tension failure of the riveted connections in levels 7 and 8 between the beams and the column in the corner where the two wings of the building join each other, initiating the damage. As a result of loss of support the slab-diaphragm in this area fails and causes a partial local collapse (Figure 8). Therefore, it was required to strengthen the slab-diaphragm over the certain area where the two wings of the building meet.

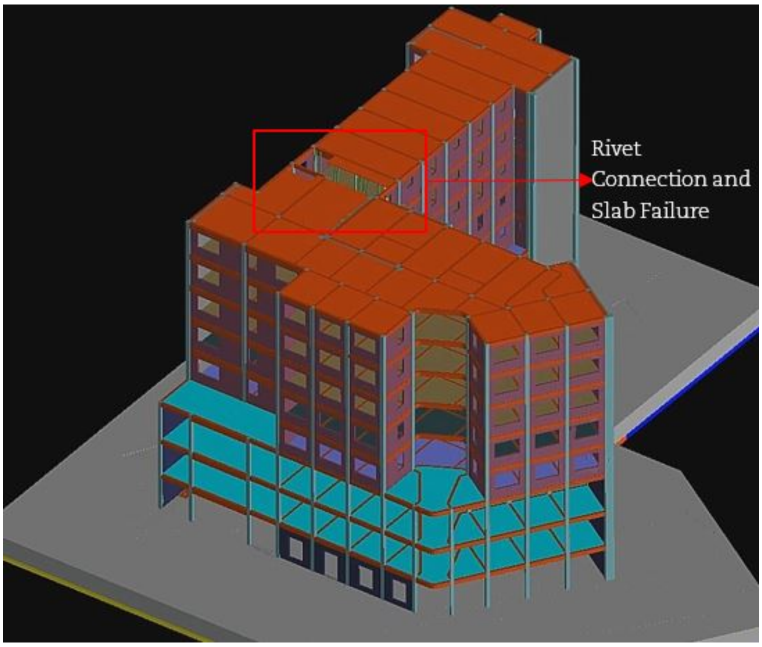


Figure 8. Partial Collapse after Continuing up the Shear Walls-70% Duzce Ground Motion.

The final scheme includes the strengthening of the slab-diaphragm in this area to all levels above the ground level using 80mm shotcrete adequately connected to the existing structure (Figure 9).

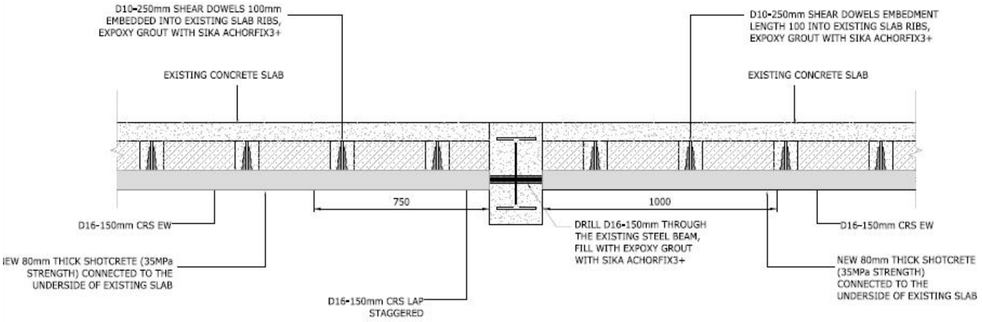


Figure 9. Slab Strengthening Detail.

6 CONCLUSION

Using the advanced capabilities of the Applied Element Method (AEM) based Extreme Loading® for structures (ELS) software we are able to create models fully utilising the concept of Performance Based Design. The AEM method is likely the future of sophisticated structural analyses available to structural engineers for damage assessment and progressive collapse analysis. It is one of the most advanced structural analysis tool capable of quantifying the level of damage sustained by a structure when it is subjected to a specific load case or ground motion. This allows the engineer to check the level of damage against the required performance objective for the particular load case. Ultimately this method gives significant time and cost savings over existing nonlinear time-history-based analysis.

This method of analysis makes evaluating multiple scenarios with multiple performance objectives (such as immediate occupancy, life safety, or collapse prevention) both practical and economical. The structure owner can easily visualize the performance and the level of damage and determine whether it is acceptable for the specific hazard under consideration. This is an enhanced advantage unavailable using many other techniques, where the performance objectives are either qualitative or quantitative but difficult to visualize by the owners.

Conventionally, the engineering industry uses a simplistic procedure for seismic assessments, which models only linear beam and column elements. This neglects the contribution of walls and slabs, leading to uneconomic and/or un-conservative results. Walls and slabs may be considered secondary members in other types of analysis but in progressive collapse analysis, walls and slabs often behave as primary members with slabs carrying load though membrane action and walls providing alternate load paths in case of loss of columns.

Considering the sophisticated modelling and analysis capabilities of AEM in ELS, it is particularly suited for historic structures where the strength of secondary elements is typically ignored in traditional modelling and analysis approaches.

In recent years progressive collapse analysis has developed into explicit requirements for redundancy in building codes all over the world.

In a comparison study, we have found that analysis using simplified finite element linear and nonlinear analysis suggested a significant increase in the strengthening scheme cost to satisfy current code requirements. Using more advanced analysis, like Extreme Loading® for Structures (ELS) software shows significant reduction on the strengthening scheme cost.

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