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Seismic Strengthening by Base Isolation — New Zealand Parliament Buildings, Wellington, New Zealand

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ABSTRACT

New Zealand Parliament Buildings have been refurbished and strengthened to resist earthquakes. Both function and heritage considerations were seen as critical to the client, the New Zealand Government. The original buildings were completed in stages between 1883 and 1922 and comprised up to five levels of unreinforced masonry bearing walls supporting concrete floors totaling 70,000 square metres of floor area. Base isolation was selected as part of the appropriate solution to protect the buildings from the large induced seismic loads (UBC zone 4 equivalent, with near fault effects).

Seismic loads were investigated firstly by a uniform risk hazard analysis to determine the maximum probable event. Secondly, a specific site hazard study, based on the proximity to a Class 1 active fault, to determine the maximum credible seismic event. The seismic loads were dominated by the MM 10 intensity expected at the site, due to a Richter magnitude 7.5 earthquake on the adjacent Wellington fault. Analysis was in stages, culminating in various multi-degree of freedom time history analyses. Base isolation was achieved by installing 417 lead rubber bearings (LRB) and high damping rubber (HDR) bearings between the foundations and superstructure. These comprised alternating layers of HDR and steel, the LRBs with lead cores. Strengthening of the foundations and superstructure was required to enhance the existing structural strength available. This was achieved conventionally with reinforced concrete and steel, taking full account of the heritage considerations.

Construction was completed largely as anticipated. The project was the largest of its type attempted in New Zealand and involved underpinning and other techniques of notable scale. The buildings were re-opened for use in early 1996 and have been acclaimed structurally and architecturally as being significant on a global scale. The structural engineers received the Premier Gold Award at the 1996 Association of Consulting Engineers New Zealand Conference.

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ABSTRACT

New Zealand Parliament Buildings have been refurbished and strengthened to resist earthquakes. The original buildings were completed in stages between 1883 and 1922 and comprised up to five levels of unreinforced masonry bearing walls supporting concrete floors totaling 70,000 square metres of floor area. Base isolation was selected as part of the solution to protect the buildings from the large induced seismic loads (UBC Zone 4 equivalent with near fault effects). A total of 417 high damping rubber (HDR) and lead rubber bearings (LRB) were installed between the foundations and superstructure. Strengthening of the foundations and superstructure was required to enhance the existing structural strength available. Construction was completed largely as anticipated. The project was the largest of its type attempted in New Zealand and involved underpinning and other techniques of notable scale. The buildings were re-opened for use in early 1996 and have been acclaimed structurally and architecturally as being significant on a global scale. The project demonstrated that base isolation can be effective in achieving conservation objectives of historic buildings.

INTRODUCTION

In 1989 the New Zealand Government decided to strengthen and refurbish Parliament House and the Parliamentary Library because of the level of earthquake risk they presented and the functional inadequacy of the existing buildings. The project consisted of Parliament House completed in 1922, the General Assembly Library West Wing completed in 1883 and the Library East Wing completed in 1899. All buildings were of unreinforced masonry bearing wall construction, vulnerable to movement of the active Wellington Fault located only 400 metres from the site.

The project brief invited eight teams of Architects and Engineers to submit proposals for options providing for: (1) maximum, (2) moderate, and (3) minimum levels of conservation. Within these conservation objectives were to be seismic performance criteria providing for either: (1) preservation of the building as a national monument, or (2) ensuring life safety of the occupants. An independent committee selected the team of Warren & Mahoney as architects and Holmes Consulting Group as structural engineers to implement a scheme which provided for moderate conservation together with a seismic performance consistent with preserving a national monument. Options to achieve these objectives were conventional shear wall strengthening or shear walls plus base isolation. The base isolation option attracted a premium of approximately 3% of the building cost. However, the client accepted the base isolation scheme because of the superior seismic performance and the greater preservation of historic features offered by base isolation.

Donovan (1991) describes the development of the seismic criteria and Poole and Clendon (1992) detail the development of structural design aspects. This paper describes the implementation of these concepts to structural analysis and the procurement of the base isolation system.

SEISMIC DESIGN CRITERIA

The site is within 400 metres of the Wellington Fault, a Class I fault estimated to be able to produce an earthquake of approximate Richter Magnitude of 7.0 to 7.5 and to produce ground shaking of MM X on the Modified Mercalli scale. The maximum ground accelerations associated with this are 0.85g. This event was defined as the Maximum Credible Event (MCE) for the site. A Maximum Probable Event (MPE) was developed from a Uniform Risk Analysis for the Wellington region. A maximum ground acceleration of 0.5g was associated with a 350 year return period for this event. Site specific spectra appropriate to a stiff site were developed for these two events, as shown in Figure 1.

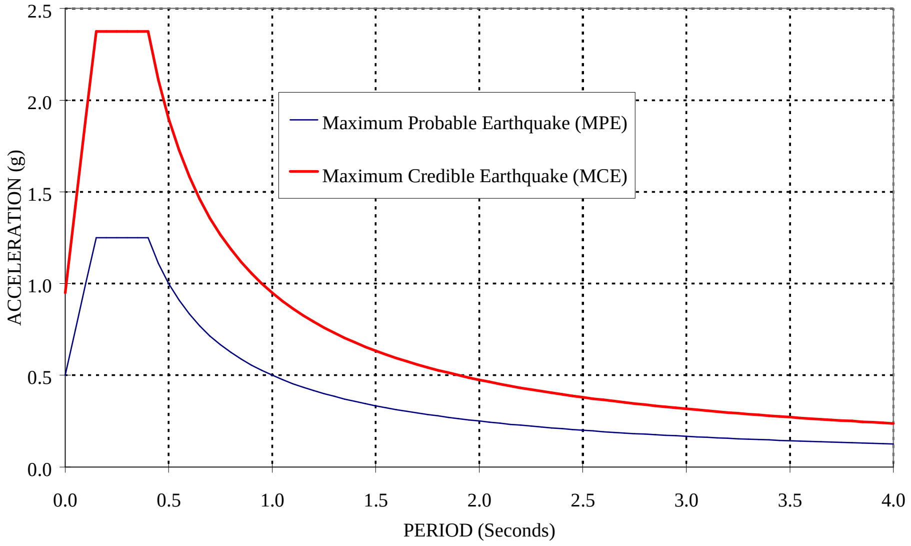

Figure 1 : 5% Damped Design Response Spectra

STRENGTHENING CONCEPT

The strengthening concept for Parliament House involved installation of lead rubber bearings in the basement level walls and columns. The existing walls were strengthened to distribute loads to the bearings. Above ground floor concrete facings were added to internal walls to increase the lateral load resistance and existing floors were strengthened to ensure adequate diaphragm action. Figure 2 shows a typical section through the basement walls.

The East Wing of the Parliamentary Library was strengthened by installing base isolation bearings, in generally the same manner as for Parliament House. The West Wing layout was not suited to a modern library and so was largely demolished and replaced with a new base isolated shear wall structure. Exterior walls of this building and portions of the interior were incorporated into the new building in the interests of conservation.

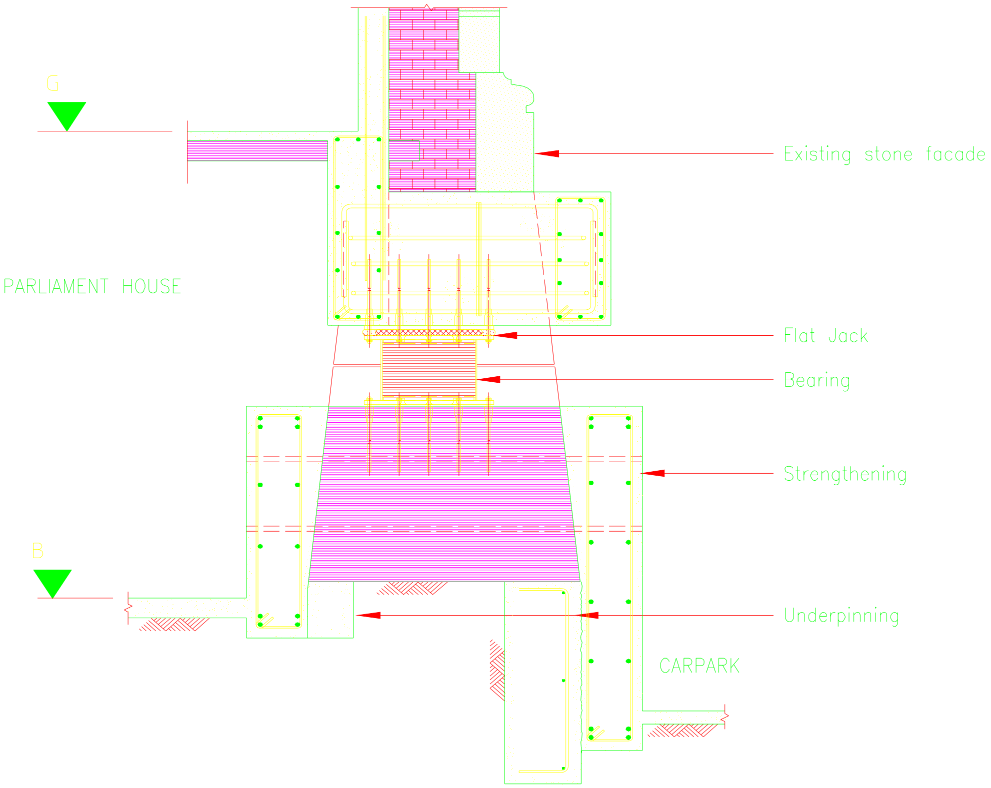

Figure 2 : Bearing Installation and Strengthening of Basement Walls

BASE ISOLATION SYSTEM

The base isolation system design was based on lead rubber bearings at all locations. At the time the initial design development was performed, in 1991, this system was the only one with an established track record in New Zealand. It was also favoured because the lead cores provided large amounts of hysteretic damping to control displacements due to near fault effects.

Lead rubber base isolation systems have been used in New Zealand from 1978 in bridges and buildings. In the first 10 years of application, design was based on a combination of requirements from codes for elastomeric bearings, empirical formulas and test data. When U.S. codes were published, AASHTO (1991) and UBC (1991), these provisions were generally adopted for base isolation design in New Zealand, with modifications to reflect local seismicity. The procedures adopted for this project generally followed UBC for analysis and testing and AASHTO for the design of the elastomeric bearings. The isolation system design was based on effective periods at MPE of between 2 and 2.5 seconds.

STRUCTURAL ANALYSIS

Three stages of structural analysis were performed during the design of the strengthening and base isolation system. Each level of analysis provided more detailed results than the preceding level. Similarly, each level of analysis served as a check on the overall response expected from the succeeding analysis.

Single Degree of Freedom Analysis

These analyses were to evaluate the most effective properties of the isolation system to maximise performance. These analyses were used to develop target values of effective period and equivalent damping of the isolation system.

Response Spectrum Analysis

An effective stiffness response spectrum analysis was performed using ETABS (1989). This analysis was based on an equivalent linear model of the isolators and a response spectrum modified to incorporate the hysteretic damping in the isolated modes. This analysis was performed for MPE event to obtain design forces for the strengthening elements.

Time History Analysis

A series of nonlinear time history analyses used ANSR-II (1979). As the superstructure was designed to remain essentially elastic during the MCE event the nonlinearity in the model was restricted to the lead rubber bearings. The superstructure was modelled as a "superelement" formed by the stiffness matrix generated from the ETABS model. This model was used to calculate maximum displacements in the isolators. Load vectors from this model at times of maximum story inertia forces were back-substituted to the ETABS model to obtain detailed element forces in the superstructure.

Three sets of acceleration time histories were used as input to the nonlinear analysis model, (1) Loma Prieta 1989 Corralitos record scaled by 1.38, (2) the 1000 year return period artificial records developed for the Oakland City Hall record (Donovan, 1991) and (3) El Centro 1979 Array 6 record scaled by 0.8. Figure 3 shows the envelope of the spectra of these time histories compared to the MCE site spectrum.

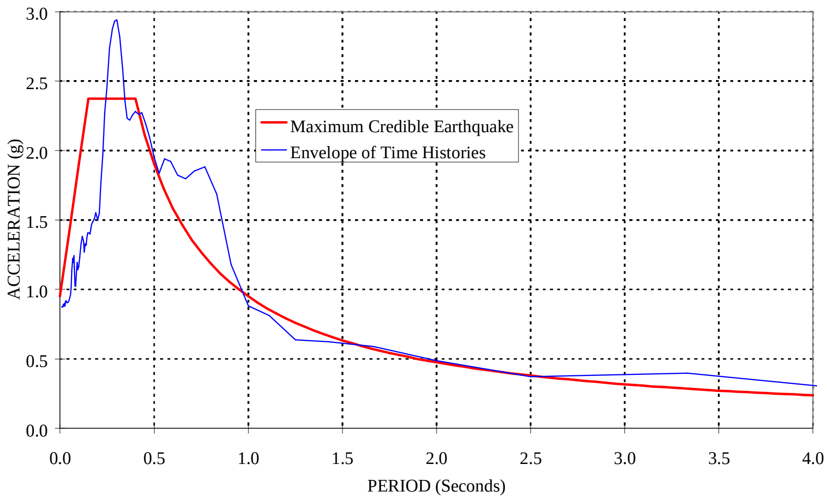

Figure 3: 5% Damped Envelope Spectra of Time Histories

The Array 6 trace was recorded in a near fault location and includes the effect of the large velocity pulse typical of near fault effects. This is manifested in the high energy content in the long period range, especially in the 230° component. This component has a spectral acceleration of 0.31g at a 1.25 second period increasing with period to a spectral acceleration of 0.4g at 3.3 seconds. The performance of a base isolation system for this type of record is contrary to the behaviour on which the principle of isolation is based in that both displacements and base shear increase with increasing period. An isolation system design based solely on this record would target an effective period of 1.25 seconds. This illustrates the importance of using multiple records with different characteristics. For example, on this project an isolation system design for

1.25 seconds would by subjected to spectral accelerations of 0.64g from the Oakland record. This acts as a check against designing to the "window" of low accelerations in the Array 6 record.

PERFORMANCE OF ISOLATED BUILDINGS

The buildings are stiff and so with strengthening but without isolation the period would be in the range of peak spectral accelerations, 1.25g for MPE and 2.4g for MCE, as shown in Figure 1 for periods between 0.15 and 0.40 seconds. The maximum base shear from the analyses of the isolated buildings, shown in Table 1, corresponds to 0.18g for the MPE and 0.25g for the MCE. This demonstrates that the isolation system is very effective in reducing inertia forces in the structure. The period shift effect accounts for most of the reduction, as forces decrease by a factor of 6 as the period increases from 0.4 seconds to 2.25 seconds. The hysteretic damping provides a further reduction of about 30%.

The displacements required to provide these force reductions are also listed in Table 1. The MPE maximum displacement of 179 mm increases to 331 mm for the MCE. The MCE displacement reflects the influence of the near fault effect in the Array 6 record.

TABLE 1

MAXIMUM DISPLACEMENTS AND BASE SHEAR COEFFICIENTS

		Parliament Building	Library East	Library West
Maximum Probable Earthquake (MPE)	Δ (mm) C (V/W)	138 0.15	142 0.18	179 0.16
Maximum Credible Earthquake (MCE)	Δ (mm) C (V/W)	351 0.23	251 0.25	331 0.22

The maximum shear distribution up the height of the buildings was derived from the results of the time history analyses and critical force vectors applied to the ETABS model to obtain maximum element forces. At the time steps when maximum base shear occurred the acceleration distribution with height tended to be approximately uniform, as shown by the dashed line in Figure 3. The maximum inertia forces in the top levels were generated by an acceleration distribution which increased with height, as shown by the solid line in Figure 3.

The results from these analyses suggest that code requirements which specify a uniform distribution of forces with height for base isolated buildings, compared to the linearly increasing distribution for non-isolated buildings, would be accurate for the lower stories but may understate the shear in the upper levels.

HARDWARE PROCUREMENT

The isolator supply formed part of the main contract for the strengthening and renovation. The base isolation specification provided two options for the isolation system: (1) a complying system where isolators were to be supplied according to the specific design used for the evaluation, or (2) an alternative system which could be demonstrated to provide at least equivalent performance, as measured by displacements and forces, to the complying system.

For the complying system, construction details for six types of lead rubber bearings were supplied. The bearings ranged from 480 mm to 630 mm in plan size and from 342 mm to 460 mm high. Quantities of each

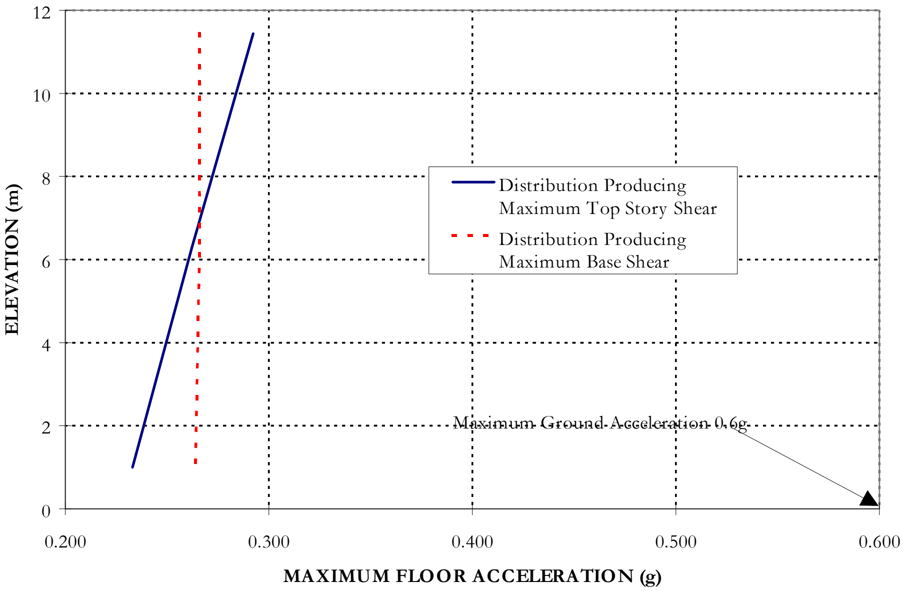

Figure 3 : Floor Acceleration Profile

type ranged from five to 119, providing a total of 417 bearings. For each bearing type a design shear force and hysteresis loop area was specified at the Total Design Displacement. The manufacturer was to adjust the design as necessary to meet the specified properties.

For alternative design, the specification provided the MPE and MCE response spectra and also the time histories and scaling factors to be used for analysis. It was required that potential suppliers demonstrate by analysis that the design actions which the bearings imposed on the superstructure and the foundations were less than or equal to those from the complying system.

The successful contractor submitted bids for both a complying system and an alternate isolation system design based on 231 high damping rubber bearings, 149 lead rubber bearings and 37 elastomeric bearings with PTFE sliding surfaces. The alternate system was offered at a bid price about 15% lower than that of the complying system. For the three buildings, the lead rubber bearings in the alternate design provided between 70% and 110% of the damping provided by the lead cores in the complying design. The alternate system also provided a significant amount of strain-dependent hysteretic damping from the HDR bearings. The net effect of this change to damping characteristics was that displacements were reduced from 15% or more while base shears ranged from the same as the complying system to 10% less.

The isolation system supplier performed a set of time history analyses to document the performance of the alternate system and supplied a full technical report. The submittals were checked by the structural engineer and peer reviewer and it was concluded that the alternate system provided enhanced seismic performance at a lower cost to the client. This system was accepted, conditional on successful completion of the prototype and production tests.

ISOLATOR TESTING

The specifications provided for testing of two prototype bearings of each type plus manufacturing quality control testing of each bearing. The prototype tests were generally based on the requirements of the UBC 1991 edition. This required 20 cycles at wind displacement, three reversed cycles at 0.25 to 1.0 times total design displacements at three vertical load levels and 10 cycles at the total design displacement. An additional static load to the total maximum displacement at minimum and maximum load was also required.

The acceptance criteria for prototype testing were based on the system adequacy requirements of the UBC plus requirements that: (1) the shear force at total design displacement be within ±10% of the design shear force, and (2) the hysteresis loop area by greater than 90% of the design area. The design values used as benchmarks for the prototype tests were those used by the bearing supplier in the submittals for the alternate system.

The quality control (production) tests were specified as compression stiffness testing on 100% of bearings plus combined compression and shear testing on not less than 20% of the bearings. The acceptance criterion required that the compressive stiffness not vary by more than ±10% from the mean values for all isolators of the same type.

The acceptance criterion based on mean compressive stiffness proved impractical for two reasons: (1) the compression stiffness is very high for laminated bearings; the apparent measured vertical stiffness was influenced by test rig stiffness and initial out of parallel of top and bottom plates such that it was difficult to obtain consistent results, and (2) the reference of measured value to mean resulted in a "moving target" as production continued, leading to the possibility that bearings initially accepted could prove to be out of specification as the mean value changed. For these reasons, the specification was modified to require combined compression and shear testing on all bearings with the acceptance criterion being that bearings tested within ±10% of the effective stiffness used in design. This procedure proved more practical and has been adopted for subsequent isolation projects.

CONCLUSIONS

The restoration of the three buildings in the New Zealand Parliament Buildings project was completed in 1996 to widespread acclaim for its adherence to conservation values and awards to the Architects and the Structural Engineers involved. The adoption of the strategy to reduce seismic forces using base isolation was a key factor in minimising superstructure strengthening to a level which was not unduly disruptive to the historic fabric of the building.

The project was the first building retrofit using base isolation in New Zealand. The successful decoupling of the unreinforced masonry buildings from their foundations to allow isolators to be installed demonstrated that construction practices are fully capable of implementing such schemes for even fragile structures. The cost penalty of isolation versus conventional strengthening, about 3% of total cost, was considered to be well worthwhile when compared to the higher level of conservation that was achieved and the improved level of earthquake safety.

The analysis techniques used were consistent with those required by U.S. codes and were able to be achieved using widely available computer software. This had the advantage that the structural engineer, isolation system supplier and peer reviewer could all validate analyses performed by the other parties.

The provision in the specification permitting alternate isolation systems to be submitted resulted in a cost saving to the project and enhanced seismic performance. There were some added costs and time involved for the structural engineer and peer reviewer to evaluate the alternate design but this did not delay the project or outweigh the cost saving.

Quality control test requirements, where acceptance was based on measured compressive stiffness within a specified tolerance of the mean value, did not prove workable. An acceptance criterion based on measured effective stiffness relative to the design values proved more practical.

The completion of this high visibility project has aided in the acceptance of base isolation as a viable technique for providing enhanced earthquake safety although its use in New Zealand continues to be confined to mainly buildings with special functional requirements, historic value or valuable contents.

ACKNOWLEDGMENTS

The successful completion of this project was a result of collaboration between all design professionals and contractors involved:

Holmes Consulting Group Ltd	Lead Structural Engineers
Warren and Mahoney Ltd	Architects
Forrell/Elsesser Engineers, Inc.	Structural Engineers (Peer Review)
Mainzeal (New Zealand) Ltd.	Main Contractors
DIS Pacific Ltd	Isolator Manufacture
Institute of Geological and Nuclear Sciences	Seismology
Dr J Berrill, University of Canterbury	

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