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Managing seismic risk: A case history of seismic retrofit for a non-ductile reinforced concrete frame high rise office building

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ABSTRACT: Managing seismic risks in existing buildings is often much more complex than for new construction. The social/economic/aesthetic/functional constraints imposed on the engineer are often more complicated to deal with than the basic engineering design considerations. To illustrate the multifaceted decision-making process involved in risk management, an actual case history has been presented using an eight-story non-ductile concrete frame office building constructed in Seal Beach, CA during the mid-1960's. The building is located adjacent to the active Newport-Inglewood fault that generated the damaging 1933 Long Beach earthquake. It serves as a vital administrative facility for Rockwell International Corporation and may not be vacated for an extended period of time without severe financial consequences to the corporation.

Previous reviews of the building by four independent firms had found the risk to life safety to be unacceptable. Through a detailed decision-making process developed by Rockwell and their consultants, strengthening schemes were reviewed. Rockwell chose base isolation combined with strengthening over all other alternatives, in order to assure life safety and to minimize operational downtime after a damaging earthquake. Key elements in the decision-making process have been identified.

1.0 INTRODUCTION

The first retrofit strengthening of a non-ductile reinforced concrete frame high-rise building using base isolation was successfully completed in 1991 on the Rockwell Corporation's World Headquarters Building in Seal Beach, CA. The decision-making process that led to selecting base isolation over other more conventional forms of retrofit strengthening is documented in this paper.

This process was not only complicated by the presence of new untested technologies, but also by the social, economic, aesthetic, and the functional constraints imposed by the building's owners and occupants. These constraints are often typical of those associated with seismic risk management in existing facilities.

2.0 BACKGROUND

The eight-story non-ductile concrete frame office building houses Rockwell International Corporation's vital administrative facilities. It was constructed in 1967 to seismic standards of the 1964 Uniform Building Code (UBC). The building has a vertical load-carrying system consisting of lightweight reinforced concrete waffle slabs supported on hard rock concrete columns and massive exterior spandrel frames. All of the columns terminate at the basement level on 1 meter (36-inch) diameter, 15m (50-foot) long drilled cast-in-place reinforced concrete piles. The exterior frames are lightly reinforced, typical of non-ductile construction of that era. The interior columns are spiral reinforced.

The building is located within 1 km (0.6 mile) of the active Newport-Inglewood fault. In 1933, the fault segment adjacent to the site ruptured, producing the damaging Long Beach earthquake, a Magnitude 6.3 event. Geologic evidence indicates the fault is capable of generating up to a Magnitude 7 event.

Past earthquake experience of the last two decades has shown that the massive non-ductile reinforced concrete frame high-rise structures with lightly confined column steel, are much more susceptible to earthquake damage than ductilely designed concrete frame structures built to the seismic provisions of the UBC since 1976.

3.0 PRELIMINARY EARTHQUAKE REVIEWS

As a normal precaution, Rockwell commissioned an earthquake safety review prior to moving the vital Corporate administrative facilities into the building in 1977. The due diligence report, prior to moving, concluded that the building did not meet the lateral force requirements of the then current 1976 UBC. However, it was concluded by the reviewer that the building would fare very well in a major earthquake due to a series of "bonus features" that had been built into the structure.

In 1982, as Rockwell expanded and increased the loads on the floors, a new review was performed to assess not only the vertical load-carrying integrity but also the lateral capacity of the structure. Under this review, it was concluded that the building did not conform to the then current seismic building code requirements, and it only possessed a quarter of the strength required to resist design earthquakes. The report also identified a potential risk to life safety as well as business continuity.

Rockwell was committed to maintaining the high value/critical administrative functions within the building and placed a priority on upgrading it for seismic safety. As a consequence, two additional independent reviews were commissioned by Rockwell in 1986 and 1987. These studies both indicated that the building had approximately 1/4 of the seismic strength that was required under then current building code standards and that the risk to life safety was unacceptable. The 1987 study further recommended the building be retrofit with either base isolation or conventional shear walls.

4.0 PROJECT REVIEW TEAM

Once convinced of a potentially serious hazard, Rockwell assembled a project review team (PRT) with the primary focus on confirming the risks and identifying the optimum plan for mitigating risks to both life and business. A classic project (matrix) management organization was employed to assure that all cost, schedule and technical objectives would be realized. Project management has long been used in the Rockwell Corporation to achieve specific objectives within a traditional (functional) organization. Rockwell's project management skills in the area of research and development have been well recognized in recent years in the pioneering projects in space including the current Shuttle Orbiter Program. These same skills in organizing and managing a project review team were applied to assess the need for and the credibility of using state-of-the-art base isolation technology in a retrofit mode on a high-rise building.

Rockwell's members of the PRT included:

1. A Program Manager, reporting directly to executive level management.
2. Operations managers, representing all aspects of the building's function and operations.
3. An internal technical consultant--a structural engineer with earthquake expertise.
4. An advisory review board, composed of senior management. The Program Manager reported project status to the review board on a regular basis.

Outside consultants were selected for the PRT to address the technical issues in areas outside of Rockwell's expertise. These outside consultants included: (1) structural engineers; (2) geotechnical engineers; (3) seismologists; (4) earthquake engineers; (5) suppliers of base isolation systems; (6) university researchers with recent state-of-the-art knowledge in: non-ductile reinforced concrete behavior in earthquake; analytical methods and techniques; and near-field earthquake effects.

Clearly the topics of: (1) base isolation retrofit, (2) seismic behavior of non-ductile reinforced concrete frames, (3) near-field ground motion effects, and (4) earthquake performance of buildings beyond minimum life safety were perceived by Rockwell as requiring advanced expertise.

5.0 OBJECTIVES OF THE PROJECT REVIEW TEAM

The objectives for the project review team were:

1. To confirm previous investigations relating to the seismic safety of the existing building.
2. To review the previously proposed seismic upgrade schemes, with particular emphasis on retrofit utilizing base isolation.
3. To define and explore additional upgrade alternatives.
4. To provide comparative analyses of all potential seismic protection schemes.
5. To support and assist program management in preparing proposals for presentation to senior executive level management.

6.0 TEAM METHODOLOGY

6.1 *Confirmation of previous findings*

The first step involved a reassessment of earthquake hazards at the site including strong ground motion, soil instability due to liquefaction, and surface fault rupture at the site. Four earthquake events having different levels of risk were considered. Both probabilistic as well as deterministic modeling procedures were used to assess the potential site-specific ground motion. The dominant seismogenic source of ground motion for the site was the nearby Newport-

Inglewood fault system, located 1 km (0.6 mile) to the southwest. The Maximum Credible Event on this fault is estimated at a magnitude of 7.0. Near-field effects (e.g., fling of the fault) were considered in the estimate of ground motions contributed by this fault.

The potentials for liquefaction as well as for surface fault rupture at the site were reviewed based on available literature and simplified analytical procedures. The potential risks from these two forms of geoseismic hazard were found to be relatively low.

The building structure and its foundation system were reviewed in two stages: the first involved a preliminary analysis of the design capacity of the existing structure under current seismic building code provisions as well as the four estimated earthquakes. Based on these preliminary results, experts in the field of earthquake behavior of non-ductile reinforced concrete frame structures were consulted for their opinion on the reserve capacity and ultimate failure mode of the existing structure. In the second step of review, non-linear dynamic analyses were performed on the structure, including its foundation system to assess the earthquake behavior under two levels of earthquake exposure--the Maximum Credible Event from the nearby Newport-Inglewood fault and a distant Magnitude 8+ San Andreas event having a high probability of occurrence during the life of the facility.

The results of the review of the site hazards revealed that the ground motion associated with the Magnitude 7 event was significantly greater in amplitude than estimated in the previous investigations and 50% greater than implied by the current building code. The basic building structure was found to have insufficient strength and reserve capacity in the form of ductile behavior to safely survive the Magnitude 7 event without experiencing heavy damage and possible collapse. Thus, the building represented an unacceptable life safety risk based on current building code seismic design philosophies. Furthermore, it was found that even under an event having a 50% probability of occurrence within the next 50 years the disruption to vital corporate administrative functions within the building would be unacceptable.

6.2 *Review and identification of alternative strengthening schemes*

Based on these confirmatory findings, the PRT proceeded to review alternative strengthening schemes. Four retrofit schemes were ultimately selected for analytical comparison: (1) base isolation plus exterior diagonal bracing; (2) conventional diagonal braced frames on the exterior; (3) exterior shearwalls in the perimeter frames; and (4) jacketing of the non-ductile concrete beams and columns.

Major emphasis was placed on the base isolation concept since it represented the greatest potential for reducing the risk to life as well as business interruption. Further, base isolation represented the scheme with the greatest uncertainties in design and constructibility. The technical expertise of a base isolation manufacturer was necessary to define the physical characteristics associated with the isolator system and its limits of deformation. Based on this information, non-linear dynamic analyses were performed on the building using a preliminary design of the isolator system. These investigations revealed that under acceptable isolator deflections on the order of 30 to 35 cm (12 to 14 inches), the building structure would still experience heavy inelastic deformation that exceeded the ductile capacity of the brittle reinforcing schemes used in its construction. The alternative of base isolating the structure plus strengthening the weak perimeter frame for lateral loads proved to be a viable albeit expensive solution.

6.3 *Review of alternative approaches to strengthening*

The obvious case of "do nothing" was also considered in the analysis. The purpose for carrying this case along was to serve as a control case for comparison.

Rockwell's team independently reviewed the alternative of relocating all vital functions and personnel from the existing building to a new facility at a remote site far enough away that it would not experience the same ground motion hazards, but found this option to be prohibitively expensive.

6.4 *Levels of risk*

In order to assess the alternative strengthening schemes, levels of risk were defined in terms of life loss, property damage, and business continuity. As a minimum, all retrofit schemes were to provide for life safety as implied in current building code seismic provisions.

In order to define the level of risk associated with building damage and continuity of function, definitions of building performance were developed that could be equally understood by the engineer and the project management team.

Table 1 defines some of the damage terms used to bridge the communication gap between engineers and non-engineering managers.

6.5 *Comparative analysis of upgrade schemes*

Table 2 illustrates the comparison of the alternative retrofit upgrade schemes in qualitative or subjective terms that may be translated through Table 1 to quantitative or numerical terms. Table 2 forms a matrix of four retrofit schemes under a single Maximum Credible Earthquake scenario.

Other non-quantifiable factors of significance in the decision-making process included:

1. Dollar cost associated with life loss and bodily injury.
2. Lost business opportunities, present and future.
3. Impact on reputation or image of the corporation.
4. Loss of confidence in the building safety by its occupants.

Figure 1 illustrates the quantifiable dollar losses associated with earthquake under each of the retrofit solutions as well as the do-nothing alternative. Superimposed on this figure is the estimated retrofit costs for each scheme.

7.0 DECISION-MAKING PROCESS

The decision-making process associated with selecting the optimum solution involved prioritizing the many factors identified by the PRT and weighting them according to their relative importance.

The key factors selected by Rockwell were ranked highest priority first, as follows:

1. Life safety and bodily injury.
2. Business interruption of vital administrative operations.
3. Technical uncertainties associated with the retrofit strengthening concept.
4. Disruption of vital building functions during construction.
5. Comparative dollar losses as a consequence of earthquake.
6. Total project construction costs.
7. Economic payback (protection vs. cost).
8. Aesthetic impact of the mitigative scheme.

7.1 *Mitigating technical uncertainties in base isolation*

As seen from Table 2 and Figure 1, base isolation with retrofit strengthening of the exterior frame of the building provided the greatest risk reduction. However, the technical uncertainties associated with the new state-of-the-art technology of base isolation, as applied to an existing building, raised questions about the viability of the system. The retrofit concept involved supporting and cutting columns of the building at the first floor level and inserting rubber isolators into the column joint while the building was fully occupied. The construction process would be highly disruptive to activities on the first floor of the building and could also impact egress and exiting of the building for occupants on the other floors. The issue of constructibility was resolved by consultation with experienced U.S. contractors in base isolation retrofit. Rockwell's team also visited the Salt Lake City and County Administration Building to witness the completed upgrade of a historic building using base isolation.

The uncertainties associated with the new technology of base isolation concerning behavior under earthquake were resolved by: (1) review of recent records of earthquake behavior in base isolated buildings in New Zealand and Japan; (2) extensive research sponsored by the National Science Foundation at the university level on base isolation systems illustrating the reliability of the system under simulated earthquake loading conditions; and (3) the recent new construction using base isolation in Southern California.

The analytical tools and techniques for modeling the non-linear behavior of the building structure and its supporting isolator system brought a high degree of certainty to the predictive as well as the design processes. Dynamic earthquake analysis with non-linear modeling procedures had come to maturity in both the structural engineering practice as well as in the aerospace industry, and the results were well accepted by the management team.

8.0 DECISION TO BASE ISOLATE PLUS STRENGTHEN

In the end, the decision was made by Rockwell to base isolate and strengthen the building primarily in order to (1) ensure life safety, (2) minimize operational downtime after an earthquake, and (3) minimize operational disturbances during construction in the areas above the plane of isolation. It was felt that the few technical uncertainties associated with base isolation were acceptable or could be mitigated with additional engineering and testing.

Other considerations such as aesthetics and economics were important, but management was confident that the project review team had adequately addressed these elements.

9.0 CONCLUSION - LESSONS LEARNED

The base isolation and strengthening of Rockwell's building was completed in 1991. The project is considered a success on all counts. It received the American Society of Civil Engineers Award of Merit and numerous technical papers have documented the state-of-the-art engineering which made the project possible. Most importantly, Rockwell remains pleased with their decision and considers the project a sound investment. In 1992, Rockwell's executive staff was moved into the building and it was renamed the Rockwell International World Headquarters.

9.1 *The project review team*

The project review team was assembled using a classic matrix management organization. A Program Manager is at once the focus of all project activity, and is empowered to cross internal and external organizational boundaries on all project matters. Under such conditions, clear, timely and knowledgeable decisions are assured. It is worth noting that the PRT was highly successful despite the fact that Rockwell had no previous experience in seismic structural retrofit, let alone the use of non-conventional techniques such as base isolation. The project (matrix) management techniques employed have a long history of success in space exploration and on other state-of-the-art technical endeavors.

9.2 *Common body of language*

A common language was developed and agreed upon early in the project to facilitate communication on earthquake risks and the behavior of the building and its contents. These written definitions remained unaltered throughout the review and decision-making phases. This consistent terminology enabled engineers and managers to easily communicate on technical and performance issues.

9.3 *Educating the owner*

As an integral part of the decision-making process, Rockwell's review team and management were thoroughly educated on key earthquake engineering concepts. Most notably were: (1) the probabilistic approach to earthquake hazard prediction; (2) conditions resulting in post-earthquake shutdown by local building officials; (3) areas of engineering uncertainty in predicting seismic structural behavior.

9.4 *Comparative analysis*

A thorough comparative analysis of the alternative retrofit upgrade schemes was found to be absolutely necessary. Only by providing alternative retrofit schemes could the optimum solution be selected. Furthermore, the alternatives provided a second solution if the number 1 choice, base isolation with strengthening, was either too costly or had too many unknowns to be acceptable.

The alternate schemes also provided management with an understanding of the differences in performance and associated costs between one retrofit scheme and the other. Management might not have accepted the technical risks associated with state-of-the-art base isolation unless all other avenues of retrofit as well as relocation had been explored.

9.5 *Performance specification*

The review and decision-making process described in this paper produced a key decision with a rational basis. That decision was supported by both technical and economic analyses, yet was described in terminology understood by engineers and managers alike. Management understood clearly "what they were buying" with the base isolation retrofit.

Furthermore, the process led easily to preparation of a performance specification for final upgrade design. The owner could specify both the structural scheme and the desired earthquake performance. These could in turn be translated into engineering design criteria with a reasonable assurance that the desired performance would be achievable.

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Table 1. Example of Earthquake Damage Definitions

Property Damage - Non-Structural:

	Equipment Damage	Ceiling Tile & Lights Collapse
Minimal	<1%	Few Tiles
Minor	3%	5% of Area
Moderate	10%	20% of Area
Major/Extensive	>20%	>40% of Area

Property Damage - Structural:

2% -	Limited to non-structural and architectural (glass partitions, ceilings, paint)
10% -	Cracking in structural beams and columns that requires repair with epoxy pressure grouting; building may require temporary shutdown for repairs
40%+ -	Potential for partial or total collapse, possible condemnation of building; vital administrative functions must be relocated and access to building may not be allowed.

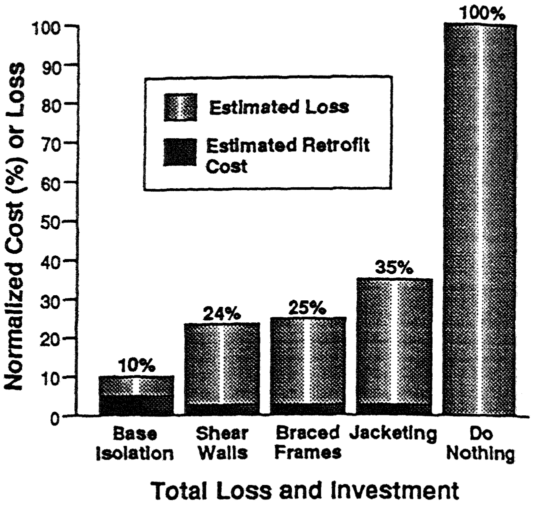

Figure 1 - Risk assessment summary in terms of quantifiable costs

Table 2. Comparison of Alternative Retrofit Schemes

Partial List of Seismic Risks @ MCE	#1 Base Isolation	#2 Braced Frames	#3 External Shearwalls	#4 Jacketing	Do Nothing
• Life Safety - Injury	Minor	Moderate	Moderate	Moderate	Extensive
• Life Loss	Not Expected	Not Expected	Not Expected	Not Expected	Some
• Equipment Damage	Minor	Moderate	Moderate	Moderate	Extensive
• Business Int.	Hours-Days	Weeks	Weeks	Weeks-Months	Months or Relocation
Construction					
• Business Impact	Low	Medium	Medium	High	--
• Architectural Impact	Low-Mod.	Low-Mod.	High	Low	--
• Schedule (Years)	3	1.75	2	1.5	--
• Project Cost (Ratios)	2.2	1.0	1.2	1.0	--
Impact of Eng. Uncertainties					
• Ground Motion	High	Medium	Medium	Low	--
• Design & Analysis	Low	Low	Low	Low	--
• Constructibility	Medium	Low	Low	Medium	--
History of Performance in Earthquakes	Some	Moderate	Extensive	Some	Extensive