Analysis of Phasing Seismic Retrofits: A Case Study

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Building performance and safety have always been a high concern in seismic areas, especially as certain building configurations and designs have proven inadequate and dangerous in large earthquakes. Building failures due to earthquake forces are combated by local seismic ordinances, which describe the types of buildings at risk and mandate when they are required to be seismically retrofitted. This paper investigates the architecture, engineering, and construction (AEC) industry and the necessity of seismically retrofitting buildings, particularly soft story wood frame, non-ductile concrete, and welded steel moment frame structures. This case study focuses on the voluntary seismic retrofit of a high-rise building in San Francisco, CA that was split into five project phases, and how the phasing impacted the structure, the client, and the general contractor. Through informal interviews with the project team, the phasing plan was evaluated to determine if the retrofit created a deeper understanding of the building structurally, allowed flexibility within the execution of the retrofit, and influenced parties' risks. These findings are useful in demonstrating how phasing a retrofit can be advantageous and disadvantageous in future seismic retrofits.

Keywords: Seismic Retrofit, Welded Steel Moment Frame, Seismic Ordinance, Structural Engineering, Construction Phasing

Introduction

In 2007, earthquake scientists led by the United States Geological Survey (USGS), California Geological Survey (CGS), and Southern California Earthquake Center (SCEC) estimated that there is a 63% probability of a magnitude 6.7 or greater earthquake in the Bay Area in the next 30 years (U.S. Geological Survey, 2021). As the potential threat of a large earthquake is pressing, so is the necessity for owners, engineers, and contractors to be proactive and seismically retrofit the Bay Area. There are several types of buildings that could benefit from phasing and will be in the next generation of seismic ordinances. These include wood framed soft story, non-ductile concrete, and welded steel moment frame buildings. This paper explores a unique contracting approach to seismic retrofit projects, analyzing a retrofit project that was performed in project phases. But firstly, it is important to understand these types of buildings and why they need to be retrofitted.

Background

The high-rise commercial building in San Francisco's Financial District that this case study analyzes was a uniquely phased retrofit project. The building's structure was composed of concrete and welded steel moment frames. The seismic retrofit consisted of strengthening the welded steel moment frame by installing fluid viscous dampers with gusset plates and beam stiffeners at the four corners of the building up to the 16th floor. The structural work also included removing and re-welding the existing full penetration welds at critical beam-column connections on each floor. It was a design-build project with a guaranteed maximum price budget that totaled about $52 million. The retrofit was completed with the building fully occupied and in project phases of 3-4 floors each. Each phase is approached with a separate contract so that the retrofit of the entire building is made up of five different project phases. The first phase began in 2017. As of 2021, phase 4 is currently in construction, with the next and final phase in preconstruction. The distribution of floors in each phase is represented in the figure below. The five colors represent the five phases and demonstrate how the floors were retrofitted out of order.

Figure 2. Project phases by color (Clip Art Avenue, 2021)

The phased manner of this seismic retrofit creates many interesting advantages and disadvantages for the building, client, and general contractor. This case study explores those advantages and disadvantages and focuses on three main topics: structure, flexibility, and risk.

Literature Review

Soft Story Wood Frame Buildings

In 2013, the Mandatory Soft Story Retrofit Program (MSSP) was created "to ensure the safety and resilience of San Francisco's housing stock through the retrofit of older, wood framed, multi-family buildings with a soft-story condition" (Department of Building Inspection, 2021). Soft story buildings are those with significantly less bracing on one story. Soft story wood framed buildings usually include those with tuck-under parking buildings, buildings with multiple garage doors, and buildings with large retail windows (Wood-Frame Soft-Story Structures, 2021). The 1994 Northridge earthquake exposed the dangers of soft story wood frame buildings; many could not withstand the lateral forces and collapsed. The retrofitting of soft story wood frame buildings looks different on each building but usually involves adding plywood shear walls or steel moment frames to supplement the soft or weak story (Wood-Frame Soft-Story Structures, 2021). Most municipalities in California, including San Francisco, now have seismic ordinances in place for soft story wood frame buildings.

Non-Ductile Concrete Structures (NDC)

Another major type of building that is at risk of failure during an earthquake is non-ductile concrete (NDC) structures. Non-ductile reinforced concrete buildings are those that are inflexible and brittle. The dangers of NDC buildings were made apparent in the 1985 Mexico City earthquake, the 1994 Northridge earthquake, the 1995 Great Hanshin earthquake, the 2011 Christchurch earthquake, and the 2016 Kumamoto earthquake (Non-Ductile Concrete Structures, 2021). From these earthquakes, it was determined that structural failures occurred due to inadequate confinement of the concrete core within the beams, columns, and joints (Non-Ductile Concrete Structures, 2021). NDC structures that have limited reinforcing steel in the column, joint, and wall details, and with configurations that concentrate stress in those same locations, are susceptible to damage and failure when subjected to earthquake forces (Non-Ductile Concrete Structures, 2021). With too little steel reinforcement to form a confining cage, the concrete can crack and crush, causing the concrete pieces to spall and lose their ability to support the load (Non-Ductile Concrete Buildings, 2018). This was observed in the 1994 Northridge earthquake when seismic movement caused the flange-to-flange weld connections to fracture, which propagated through to the columns. This brittle failure in NDC buildings is extremely dangerous because, in a large earthquake, it can cause sudden failure and collapse of a building with no warning or time for occupants to evacuate.

NDC buildings are typically concrete buildings that were built prior to the 1976 Uniform Building Code. According to the initial estimate by the Concrete Coalition at the Earthquake Engineering Research Institute, there are approximately 3,200 NDC buildings in San Francisco alone (Evaluate and Retrofit Non-Ductile Concrete Buildings, 2021). However, the San Francisco municipality has not yet issued a seismic ordinance requiring the retrofit of non-ductile concrete buildings. Regardless, many building owners are taking it upon themselves to voluntarily seismic retrofit their NDC buildings, in good faith and anticipation of a forthcoming seismic ordinance.

Depending on the engineer's evaluation, there are several prescriptions to seismically retrofit a non-ductile concrete building. While every NDC seismic retrofit is vastly unique, the general principle of these seismic retrofits is to transfer the lateral load from the concrete core to the lateral-force resisting systems in order to strengthen the building's diaphragm. This can be done by adding braced frames, moment frames, or shear walls to the existing building. Additionally, wrapping the concrete columns in fiberglass can help to improve the strength and loading capacity of the columns. There are many types of stiffeners, lateral-force restraining systems, and engineering concepts that can be combined and applied to seismically retrofit an NDC building.

Welded Steel Moment Frames (WSMF)

Welded steel moment frames (WSMF), specifically those constructed before the 1994 Northridge earthquake, are also at risk in the event of a large earthquake. WSMF first became popular in the 1960s, and like NDC's, pre-Northridge WSMF buildings were inherently flexible and designed to sway in an earthquake (Seismic Retrofit Ordinances in California, 2021). Many modern welded steel moment frame buildings sustained significant damage in the 1994 Northridge earthquake and 1995 Kobe earthquake. Additionally, some structures in the San Francisco Bay Area were found to have similar fracture damage, most likely from the 1989 Loma Prieta earthquake. After the 1994 Northridge earthquake, building standards as recommended by the FEMA/SAC were incorporated for the connection design and fabrication processes of WSMF buildings (A Policy Guide to Steel Moment-Frame Construction, 2000). Thus, WSMF's constructed in 1964-1994 are more vulnerable to earthquake damage.

These earthquakes caused brittle fracturing of the steel frames at the welded joints between beams and columns. The particular issue is the style of connection that can concentrate high stress at the weakest points. And, because the cost of labor increased in relation to the cost of materials, engineers adopted designs to minimize the number of connections in each building, which in turn created larger members and increased loads on connections. Additionally, new welding techniques that were adopted to make the connections faster, also made the welds more susceptible to cracking. Lastly, the steel industry began to produce steel with higher strength, unbeknownst to the designers. Thus, connections were not re-engineered and were not of adequate strength to match the newer steel, increasing their vulnerability (A Policy Guide to Steel Moment-Frame Construction, 2000). The main risk with WSMF is fracturing at the welded joints. However, these fractures can further cause damage to bolted joints, which can result in the complete severing of beams or columns, creating the potential for a localized collapse. However, no WSMF in the United States has ever collapsed from earthquake damage.

Like any other building, there are many ways WSMF buildings can be seismically retrofitted and strengthened. One method to upgrade connections is to bolt or weld new plates onto the beams and columns to change the connection shape and reduce stress concentrations. Another option is to add steel braces, masonry, or concrete walls to stiffen the building and reduce the amount it will sway in an earthquake. Lastly, energy dissipation systems, like fluid viscous dampers or hydraulic cylinders, convert the earthquake's energy into heat.

City	Wood-Frame Soft Story Structures	Non-Ductile Concrete Structures	Non-Ductile Steel Structures
Alameda	✓		
Berkeley	✓		
Beverly Hills	✓	Retrofit Program In Development	
Burbank	✓	✓	✓
Fremont	✓		
Long Beach	Voluntary Program, Retrofit Program In Development	Voluntary Program, Retrofit Program In Development	
Los Angeles	✓	✓	
Oakland	✓		
Palo Alto	Retrofit Program In Development		
Pasadena	✓		
Richmond	✓		
San Francisco	✓		
Santa Monica	✓	✓	✓
Torrance	Voluntary Program, Retrofit Program In Development		
West Hollywood	✓	✓	✓

Figure 1. Cities with seismic ordinances in effect (Seismic Retrofit Ordinances in California, 2021)

Figure 1 above indicates which California municipalities have adopted seismic ordinances for wood frame soft story structures, NDC structures, and non-ductile steel (WSMF) structures.

Methodology

In order to survey the positives and negatives of the phased seismic retrofit, informal phone interviews were conducted with different members of the project team. The goals of the interviews were to gain first-hand industry insight on the major differences and caveats of the phased project. The interviews aimed to understand the structural aspects of phasing, as well as the perspective of the general contractor and the client. While they were mostly unstructured and casual conversations, the interviews generally guided the conversation towards how the different parties experienced unique impacts on engineering, flexibility, funding, and risk. The team members interviewed were the general contractors (GC) Project Manager, GC Senior Project Manager, GC Project Executive / Construction Manager, and Structural Project Engineer.

The Project Manager began this project as an Assistant Project Manager and has been in the construction industry for approximately 6 years. Her background begins with her studies at the University of San Francisco in Architecture and Community Design and focuses on project management in her internships as a student. On this seismic retrofit, she managed RFI's, submittals, buyout, subcontractor and client communications, and helped to update the schedule and budget.

The Senior Project Manager studied Construction Management at Arizona State University, has been in the construction industry for 16 years, and has been with this general contractor for over 7 years. He has worked on a wide array of projects, from seismic retrofits and new construction to horizontal developments. While 50% of his time was spent on this project, the other half was spent on a different seismic retrofit nearby. The Senior Project Manager took the lead on negotiations, scheduling, budget management, planning, and risk management.

The Project Executive / Construction Manager is the upper-level management on this project. He received a B.A. in Architecture from California Polytechnic State University-San Luis Obispo and has been in the construction industry for over 28 years, 22 of them being with this general contractor. He has a background in special user housing, MEP coordination, architectural intent and functionality, and has been involved in a number of seismic retrofits. On this project, the Project Executive / Construction Manager was the team leader, with the responsibility to the owner and the success of the project overall.

The Structural Project Engineer is the main representative for the engineering team. He received his Bachelor's and Master's degrees in civil engineering from Purdue University and is a licensed Civil Engineer and Structural Engineer. He has 6 years of experience as a Project Engineer at an engineering firm that is well established in providing corporate seismic program services such as program development and management, development of corporate seismic guidelines, pre-lease and pre-purchase evaluations, seismic evaluations and retrofits, critical equipment support structures & anchorage, and post-earthquake inspection and training. The Structural Project Engineer is responsible for the engineering, which includes performing calculations, creating the building models, providing drawings and specifications, and responding to RFI's and submittals.

Results

The main reasons why the client chose to phase construction of the seismic retrofit were because of the need to keep the building occupied, that they could not afford to fund it up front, and they wished to avoid the commitment to finish the retrofit of the entire building. In conjunction with these factors, phasing the retrofit created many unique outcomes. Based on the interviews, structural improvement, allowed flexibility, and risk were the main impacts of phasing this seismic retrofit project.

Structural

Performing the seismic retrofit on this building in five project phases impacted the building structurally in a few ways. First, due to the client's requirement for flexibility in the sequence of floors, the engineers determined that retrofitting floors out of sequence would not negatively impact the overall structure. While leaving gaps between strengthened floors does produce some concentration of deformation, this small margin of deformation greatly outweighed the overall improvement of the entire building. It was also found that there is a greater structural improvement to the entire building as the phases progressed. Even though the out-of-order sequencing of floors is unconventional and inefficient in some ways, it allows flexibility and increased seismic improvement between phases.

Additionally, phasing the project gave the client the freedom to stop the retrofit after a phase and leave the building only partially retrofitted. Stopping the project at any phase was a possibility for the client because the project is a voluntary retrofit, and each phase is permitted separately, requiring each phase of retrofitting to show that the building is continuously improved. The building has been permitted as a voluntary seismic improvement per the California Existing Building Code, which allows any voluntary seismic work to occur, provided that the work does not introduce any structural irregularities or overly increase forces on existing members. It must also demonstrate that the building performance is improved with each phase. However, the client has been dedicated to completing the retrofit over time, which has been very helpful during the design review.

Retrofitting a building in this unique phased manner has proved challenging at times for the engineering team, yet has provided valuable engineering insight. Modeling the many phases, scope changes, and iterations have provided a much better understanding of the overall behavior of the building; a behavior that wouldn't have been discovered by just designing the entire retrofit itself. Overall, this new phased approach to seismic retrofitting has shown that the building can be retrofitted out of sequence with increasing improvement after each phase, and can even be left partially retrofitted.

Flexibility

Breaking up the retrofit into different project phases gives the client control and flexibility, which is arguably the biggest advantage in using a phased project delivery method. By only completing 3 or 4 floors in each phase, the contractor's footprint in the building is minimized, and the building is capable of remaining operable and occupied. By keeping the majority of the building occupied, the client is able to maintain the majority of their revenue from the building's rent during construction. Maintaining this stream of revenue during construction is used to offset the cost of construction. Another reason why the client chose to phase the retrofit was that they couldn't fund the entire project upfront. Even though the client knew from the beginning that the seismic retrofit would be 30-35% lower in cost if they had vacated the entire building and done the retrofit all at once, they chose to pay more in construction because they could not commit to the large capital expense upfront. The retrofit was more expensive to do in project phases due to the extended amount of time, added costs of design and review from permitting each phase separately, premium in labor and materials, and lost efficiency to fabricate the steel and purchase all the dampers at once. Phasing the project also minimized financial commitment because the client maintained the freedom to be able to walk away from the retrofit at any time, as long as the current phase was completed.

The client also exercised their flexibility by keeping the building occupied and by performing the retrofit out of sequence. Retrofitting out of sequence allows the client to choose when floors are turned over for construction as well as the order that floors are retrofitted, based on floor availability. They used this opportunity to keep their tenants by moving them to different floors when their current floor was to be retrofitted. The client is also able to make changes to these decisions, within reason. Changing the sequence of floors had only a small impact on the project, as long as the flow of construction was not interrupted by differing vacating dates. This is because the dampers can be used on different floors than they were designed for even though they are fabricated custom ordered for their specific location. When the floors to be retrofitted switched phases, the dampers that were ordered for the delayed floor were able to be used on the new floor, even though the damper was about one inch short. That dimension difference was approved by the structural engineers because it was made up for in the welding of the gusset plates that the dampers attach to.

While the allowed flexibility and ability to change floor sequence and turnover is extremely advantageous for the client and their ability to continue to operate the building, it has been the cause of many delays as well. The client has pushed back a lot of floors and construction start dates due to the occupation of tenants on particular floors. Additional schedule setbacks have occurred due to the client's internal approval for funding taking longer than anticipated. All of these delays caused price increases to the owner that were caused by the extended amount of time and general conditions, the premium and cost escalation in labor and materials (including the 7% price escalation of steel due to the steel shortage), and lost efficiency. However, the potential sale of the building had an especially large schedule impact and caused the client to decide to halt construction for six months. This lull was especially disruptive to the contractor because they could not float the project team for six months. The general contractor's Superintendent, Project Manager, and Senior Project Manager were reassigned to different projects for this time, and a new Superintendent and Assistant Project Manager came onto the job once construction started again. Because the nature of the retrofit is repetitive, there was progress lost on the learning curve due to the team substitutions. However, this loss was minimized by keeping the same construction manager, labor foreman, and structural steel crew. Additionally, both the new and old project team members attend Owner, Architect, Contractor meetings to offer support and minimize any loss of information.

Risk

Phasing the project has created many distinct circumstances that have impacted the types and quantities of risk inherited by the client and the general contractor. One way the client is able to minimize their financial risk is in their overall commitment to the project. Because the voluntary retrofit can hypothetically be abandoned after any phase, the client only takes on the risk of each active phase, rather than the entire building. This allows the client to mitigate risk by protecting themselves from making a large capital investment that may later turn out to be too difficult or costly. For the general contractor, this is favorable for risk mitigation in a few ways. Like the client, the general contractor only has to take on the risk of the active phases; the risk is distributed into smaller portions over a longer period of time, with increasing predictability, efficiency, and confidence as the phases progress. Additionally, the general contractor was at a lower risk of nonpayment because the owner must be more conservative with their financial commitments. While the remaining phases being canceled at any time may seem like a large risk to the contractor, in actuality, it is almost no concern. This is because the contractor knows that the client has always been dedicated to completing the entire building and because they are not contractually or financially committed to phases before they begin. Rather than including all phases in their cash flow forecasts, they only recognize active phases. All phases before the contracts are "awarded" are treated as project leads.

However, keeping the freedom to walk away from the project has some tradeoffs. Because phasing the project increases the overall duration of the building's retrofit, and it is subject to changes in the schedule or additional delays, the client is subject to unknown cost escalations in the future. For example, the client fell subject to this risk in cost escalation when there was an unexpected steel shortage that caused the cost of steel to increase by 7%. On the other hand, the contractor doesn't experience extreme risk when the schedule is pushed back or the duration is extended. Cost escalation is leveled and billed to the owner, and the contractor hasn't lost very much on their learning curve. Additionally, during the extended delay halfway through Phase 3 in 2020, the contractor was able to negotiate with the client and receive their retention for the floors already completed while they waited for release on the remaining floors.

The last way phasing influences risk is how each party's commitments to another are bound by contract. From the beginning, it was agreed that if the client completed the entire building, they would use the same general contractor, design team, damper supplier, and structural steel subcontractor. Making this tentative commitment balances the client's risk and lowers the contractor's. For the client, the risk of committing to a weak project team is outweighed by the good relationships they build and the learning curve that is maintained. Additionally, the client would have to commit to one team even if the project was not phased. For the general contractor, this eliminates any risk of losing a phase to a competing general contractor and ensures that the key players will be consistent. While these key players are locked in, the subcontractors are not. Each phase has an individual and independent contract, which requires the general contractor to obtain three subcontractor bids for buyout. This allows the general contractor the freedom to change subcontractors between phases and to keep the subcontractor bids competitive. The multi-phase and repetitive nature of the work motivated the general contractor to keep all of the same subcontractors to maximize the learning curve, keep bids low, and improve relationships, with one exception. At the end of Phase 1, the electrical subcontractor caused a near-miss safety accident. The incident was a serious safety concern that forced the owner and general contractor to deem the subcontractor incompetent and unfit to continue on the remaining phases. Because Phase 1 was just ending and Phase 2 construction hadn't started yet, the general contractor and the owner were able to eliminate the risk of continuing with an unsafe and incompetent subcontractor and hired a new electrical contractor for the rest of the retrofit. By individually contracting each phase, the general contractor was able to remove the risk of incompetent subcontractors, which would have been more difficult or impossible to do if the entire retrofit was under a single contract.

Summary

Dividing a voluntary seismic retrofit into separate project phases is a unique project delivery approach that has various impacts on the engineering, flexibility, funding, and risk of the project. Phasing the retrofit not only creates a deeper understanding of the building's structural behavior, but also teaches us that the floors can be phased out of sequence, that there is a greater structural improvement with each additional phase, and that the building can be left only partially retrofitted. These structural findings allow for the client to have more flexibility and control over the project. The client is able to keep the building occupied during construction and is in control of the schedule and when floors are retrofitted. The general contractor is able to decrease their risk with subcontractors by contracting each phase separately. Meanwhile, the client bears the risk of price escalations from an extended schedule. While the cost of construction is more expensive for the client when split into project phases, the offset costs from keeping the building occupied, retaining control and flexibility, and risk advantages proved worth it for the client.

Conclusions

The main motivations for the client to phase this project were keeping the building occupied, avoiding funding the project upfront, and retaining the ability to cancel future phases and leave the building partially retrofitted. While phasing a seismic retrofit is unconventional and unique to this project, this phased delivery system can be utilized for future projects if circumstance and necessity fit the building, client, and contractor. Phasing a retrofit can be beneficial to voluntary retrofits, especially in the current window between seismic ordinances when a new ordinance is imminent but there is still time to get ahead. Phasing also appeals to building owners who are not bound by a tight schedule, cannot afford the entire retrofit upfront, prefer to keep the building occupied during construction, prefer to maximize flexibility, or are concerned with committing to subcontractors.

Even though this case study focuses on the seismic retrofit of a welded steel moment frame building, phasing could potentially be applied to other building types with the same or similar benefits, such as soft story moment frames and non-ductile concrete structures. This study was limited in that it was only able to analyze one specific case of retrofitting in phases. Future studies should investigate phasing on other types of buildings, like soft story wood frames or non-ductile concrete structures. Additionally, a more engineering-focused study would be a valuable perspective on the subject of phasing structural retrofits.

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