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SEISMIC RETROFIT OF HISTORIC BUILDING STRUCTURES

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ABSTRACT

Buildings with historic values are regional cultural assets worth preserving. The design technologies and building materials and methods that went into the original construction of these buildings are often drastically different from their contemporary counterparts, their structural renovation or retrofit brings forth many technical challenges to the design professional. This paper provides a general survey of the technical issues pertaining to the seismic retrofit of historic buildings, and explores various design procedures and construction methods for that purpose, including innovative technologies such as post tensioning, seismic isolation, composite wraps, etc. Special attention is given to the typical structural attributes of historic structures in terms of their structural stiffness, strength and ductility, how these parameters changed over the years, reliable methodologies for evaluating these primary structural attributes, and associated design implications for structural retrofit or hazard mitigations. Much of the discussion is based on a combination of the perspective provisions in building codes and alternative performance based approaches to meet the equilibrium, strain compatibility, and energy dissipation criteria, while a considerable weight is given to factors that influence preserving non-structural elements of historic value. A brief summary on cost implications is also provided.

Overview

Buildings with historic value are regional cultural assets worth preserving. At times, they also represent a potential source of revenue and stimulus for the economical revitalization of their neighborhoods. The factors used to classify a building as historic may vary in different countries and cultures, so obviously not every aged building falls into historical or monumental category. In United States, a building is historic if it is at least 50 years old, and is listed in or potentially eligible for the National Register of Historic Places and/or a state or local register as an individual structure, or as a contributing structure in a district. In prevailing practice, older structures are demolished and replaced by modern buildings due to economical and performance reasons, unless they can be claimed historic.

The retrofit process is a general term that may consist of a variety of treatments, including: preservation, rehabilitation, restoration and reconstruction (Kelly, 1996). Preservation is defined as the process of applying measures to sustain the existing form, integrity, and materials of a historic property. Rehabilitation refers to the process of creating new application

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for a property through repair, alterations and additions while preserving those features which convey its historical, cultural, or architectural values. Restoration is the process of accurately restoring a property as it existed at a particular period of time. Reconstruction is described as the act of replicating a property at a specific period of time. Selecting the appropriate treatment strategy is a great challenge involved in the retrofit process and must be determined individually for each project.

Depending on project objectives, preservation and renovation of historic buildings may involve an array of diverse technical considerations, such as fire life safety, geotechnical hazards and remedies, weathering and water infiltration, structural performance under earthquake and wind loads, etc. Since the design methodology and building materials and methods that went into the original construction of these buildings are often drastically different from their contemporary counterparts, their structural renovation or retrofit brings forth many technical challenges to A/E design professionals.

Evolution of building materials

Building materials have evolved gradually throughout the construction history, and the pace of the evolution is accelerated throughout the past century. Advancements in material engineering and metallurgy, invention of plastics and fiber reinforced composites, and innovations in production and treatment of existing building materials are some of the major causes of old and contemporary building material differences. Improvements in conventional building materials used both in historic and contemporary structures are described as:

Masonry, stone, and adobe buildings

Bearing wall buildings were the dominant type of structures till late years of nineteenth century, when they were replaced by steel frame skeleton as the typical structural form in large buildings. In modern construction, masonry buildings are limited to certain building types and special locations. Natural stone has not changed, while adobe or bricks have slightly evolved to stronger, more durable building materials with consistent shapes and sizes. Design and construction techniques for masonry buildings are improved by using stronger mortar, and reinforcements to provide more resistance and continuity. Application of concrete filled blocks is also a major improvement in building masonry structures.

Wood and timber

Wood, as a natural building material, has not been subjected to any major change, but modern technology provides strength grading methods, wooden panel products, preservation treatment process and wood protection.

Concrete

Concrete has been subjected to significant evolution during twentieth century. Improved ingredients, quality control, preparing, and casting process offered stronger and more durable concretes. Improvements in concrete technology, application of additives, plasticizers, and improved cements provide light weight, high strength, high workability, shrinkage-compensation, low porosity, and fiber reinforced types of concrete.

Hot-rolled reinforcing steel

Reinforcing steel has evolved considerably regarding the material properties and shape. Reinforcement bars initially had square cross-sections, high carbon content, and smooth surface, where new ribbed, reinforcement bars with limited carbon content provide more ductility and stronger bond between the steel reinforcement and concrete.

Structural steel

Overall strength of structural steel was improved within past century (See Table 1). Section dimensions and properties of steel shapes have also been changed and a number of shapes are considered obsolete and they are no longer produced. Difference in strength, ductility and weldability must be considered in the retrofit design process.

Table 1: ASTM steel specifications (Handbook of Steel Construction, 7th Edition, CISC, 2000).

Designation	Date Published	Yield Strength		Tensile Strength (F_u)	
		ksi	MPa	ksi	MPa
A7 (bridges) A9 (buildings)	1914*	½ F_u	½ F_u	55 - 65	380 - 450
	1924	½ $F_u \geq 30$	½ $F_u \geq 210$	55 - 65	380 - 450
	1934	½ $F_u \geq 33$	½ $F_u \geq 230$	60 - 72	410 - 500
A373	1954	32	220	58 - 75	400 - 520
A242	1955	50	350	70	480
A36	1960	36	250	60 - 80	410 - 550
A440	1959	50	350	70	480
A441	1960	50	350	70	480
A572 grade 50	1966	50	345	65	450
A588	1968	50	345	70	485
A992	1998	50 min. to 65 max.	345 min. to 450 max.	65	450

Practice and design concepts

Building codes have been constantly updated in past decades on the basis of various lessons learned from previous failures (especially earthquake related failures). Advances in computer programs and hardware have drastically changed the way we do structural analysis and design. As a rule, newer provisions tend to prescribe better continuity for seismic loadings, provide more redundancy in structural system, and they exploit inelastic structural capacities to absorb and dissipate earthquake loads.

Such contemporary code requirements and engineering knowledge base were not available to designers and builders at the time historic buildings were typically designed and constructed without detailed assessment of the probabilistic magnitude of loading (especially load cases related to wind or earthquake) or clear knowledge on structural behavior. Design methodologies were also quite limited in past days, when engineers were required to perform hand calculations with numerous estimations in the process. Older design concepts required that working stresses remain within elastic limits. Higher engineering approximations accompanied by older design concepts, resulted in over-designed structural members which do not necessarily improve seismic behavior, but they usually add to dead loads.

Older design concepts mostly focused on the effects of gravity loads and they did not dedicate enough attention to provide adequate lateral resistance and ductility. Most of historic buildings provide limited ductility and continuity, especially when subjected to seismic loading. Unreinforced bearing walls provide limited resistance against lateral loading and a high potential of discontinuity at corners or connection to the roof. It is very common to notice historic reinforced concrete building with discontinued flexural reinforcements, no transverse reinforcement in beam-column joint zones and minimal confinement in columns.

Retrofit process requires local modification of components, minimizing structural irregularities (in mass and stiffness), structural stiffening, structural strengthening, mass reduction and seismic isolation to improve the structural performance and comply with current building codes (i.e. FEMA356, IBC2003, UBC1997). Performance objectives used for historic retrofit are similar to general objectives used in the performance based engineering context, but with extra constraints to preserving the historic fabric along with the structure itself.

In most cases, the façade and fixtures are of historic value and preserving them requires limiting deformation imposed by seismic loads. Limiting deformations is in contrast with the newer design philosophies that exploit the structural ductility to reduce the required strength. In seismic retrofit of historic buildings both the global strength and stiffness must be increased to minimize the deformation and damage to the historic fabric.

Challenges of retrofitting historic fabric

Minimizing noise, disturbance, and damage to the surrounding buildings and providing temporary shoring and support are typical challenges involved in most retrofit projects. Depending on the extends of retrofitting, assessed risk, technical limitations, structural historic value, and economical constraints, the preferred retrofit strategies are studied and prioritized to preserve the authenticity of historic fabrication and minimize removal of architectural material:

No penetration of building envelope

The process does not require any destructive procedure so the historic fabrication remains untouched (e.g. composite wraps or chemical treatment). This approach is only applicable to very limited cases since structural components are mostly either embedded in or covered by the finishing.

Penetration without breakage

The structural component subjected to retrofitting is accessible, and the retrofit process only requires drilling holes (e.g. micro piles, epoxy injection, post tensioning).

Breakage with repair

In many cases, some destructive procedures are required to access the structural component or to perform retrofit process (e.g. fixing and improving welded connections or installation of base-isolators).

Replace

In cases structural components can not be improved to meet retrofitting objectives or the damage or deterioration could not be repaired, components are replaced. Replacement process requires special attention to providing support for the rest of the building, isolating the component, and maintaining continuity.

Rebuild

In cases a feasible retrofitting solution can not be found, the historic building is reconstructed, partially or as a whole. This option imposes greater economical burden and the loss of authenticity may have impacts on historic and cultural values. Typically rehabilitation of historic buildings requires new structural members and preservation of historic fabric is accomplished by hiding the new structural members or by exposing them as admittedly new elements in the building's history. Often, the exposure of new structural members is preferred because alterations of this kind are reversible and they could conceivably be undone at a future time with no loss of historic fabric to the building.

Innovative technologies for historic preservation

Modern materials and equipment provide many retrofit options to improve the behavior of structural system, global strength, stiffness or mitigate the seismic hazards. Some of the commonly used techniques in retrofitting are listed below:

Post tensioning

Post tensioning is considered one of the potentially efficient retrofit options for reinforced concrete or masonry buildings, providing strength and ductility to the overall structure with minimal intrusion. Masonry has a relatively large compressive strength but only a low tensile strength. Hence, it is most effective in carrying gravity loads. However, in-plane shear and out-of-plane lateral loads induce high levels of tensile stress also. Commonly, these induced tensile stresses exceed the compressive stresses and reinforcing (commonly with steel members) must be added to provide the necessary strength and ductility. The level of compressive stresses can be significantly raised by post-tensioning the reinforcing steel and the more brittle tensile failures avoided. Basically, a core hole is placed down through the masonry wall and a high-strength steel rod (or tendon) is inserted. The bottom of the rod is anchored in the floor or foundation. A jack is then used at the top of the wall to place high levels of tensile force in the rod.

Base isolation

Base isolators are used to decouple the building response from the ground motion and in the event of a major earthquake, base isolation will greatly reduce structural and architectural damage, mostly by shifting the structure natural period (Figure 1). The two basic types of isolation systems that have been employed are elastomeric bearings (using natural rubber or neoprene) and the sliders (Teflon and stainless steel).

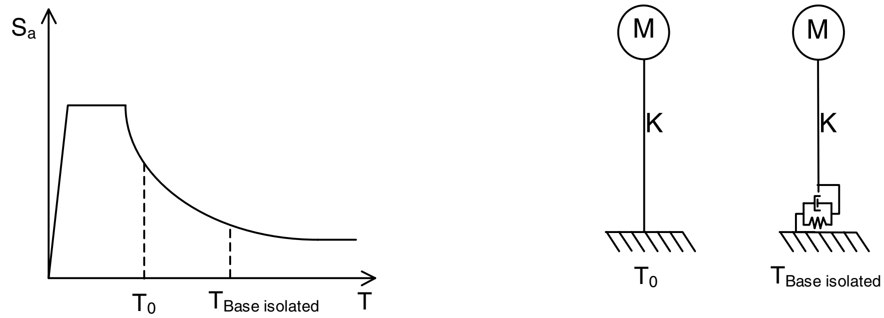

Figure 1: Influence of base isolators on earthquake loads

Composite wraps

Composite wraps or carbon fiber jackets are used to strengthen and add ductility to reinforced concrete and masonry components without requiring any penetration. Composite wraps are most effective on reinforced concrete columns (both in rectangular and circular forms) by providing additional confinement.

Micro-piles

Micro-piles are utilized in foundation rehabilitation and seismic retrofitting projects to enhance the foundation ultimate capacity and reduce foundation deflection (e.g. LSD church on Wilshire Blvd.).

Epoxy

Epoxy is one of the most versatile materials used in structural repair and retrofitting and it is used as a sealant, adhesive or mortar (Freeman House). One of the major use of epoxy is providing binding between reinforcement and concrete to restore bond degradation or provide anchorage for new concrete.

Code requirements, preservation policies, and developer incentive

Rehabilitation provisions require selecting the rehabilitation objectives and acquiring current building information prior to performing rehabilitation design. It should be noted that codes (i.e. FEMA356, IBC2003) covering historic buildings allow some amount of flexibility in required performance, depending on the effect of rehabilitation on important historic features, to the point that the minimum seismic requirements should be matched with a rehabilitation objective. In development of initial risk mitigation strategies, consideration must be first given to investigating the possibility of minimal impact to the architectural and historic value of the building and its fabric.

Acquiring as-built and current condition of the building requires comprehensive field observation, review of structural drawings and codes form the period of construction (if available), examination by means of standard test equipment and procedures and non-destructive testing (if applicable). Building configuration, component properties, geotechnical characterization, and information regarding adjacent buildings must be collected. An analysis of the building, including rehabilitation measures, shall be performed, and the results of the analysis shall be evaluated in accordance with the retrofit objectives.

Cost implications, comparison of retrofitting versus new construction premium

Many factors affect the cost for retrofitting a historic structure. It requires information collection, special engineering procedures, trained workers and unconventional building materials. Depending on the project objectives, the retrofit design may target one of four performance levels (i.e. collapse prevention, life safety, immediate occupancy, and operational), where the actual outcome of retrofitting may not meet higher performance objectives. In many cases, retrofitting expenses is comparable with or even exceed new construction premium. For historical building, economy is not the only factor for the final decision on performing retrofit or reconstruction and sociopolitical and legal factors are also involved. The primary role of architects and engineers in the decision is providing economical and technical information, while the final decision relies highly on regulations, politics, and historic values.

Example case study

A case study is provided by structural retrofit of Frank Lloyd Wright's Freeman House in the City of Hollywood. The Freeman House was constructed in 1924 by using the textile block wall system. Wright's development of concrete blocks into what he referred to as "textile block system" is part of his approach in which the building materials and methods are signatures of his design. Precast concrete textile blocks were constructed onsite and were stacked dry without mortar joints. There is a horizontal and vertical grid of reinforcing encased in grout tube between blocks. The freeman house is approximately 2500 square feet, including two floor levels and a roof terrace.

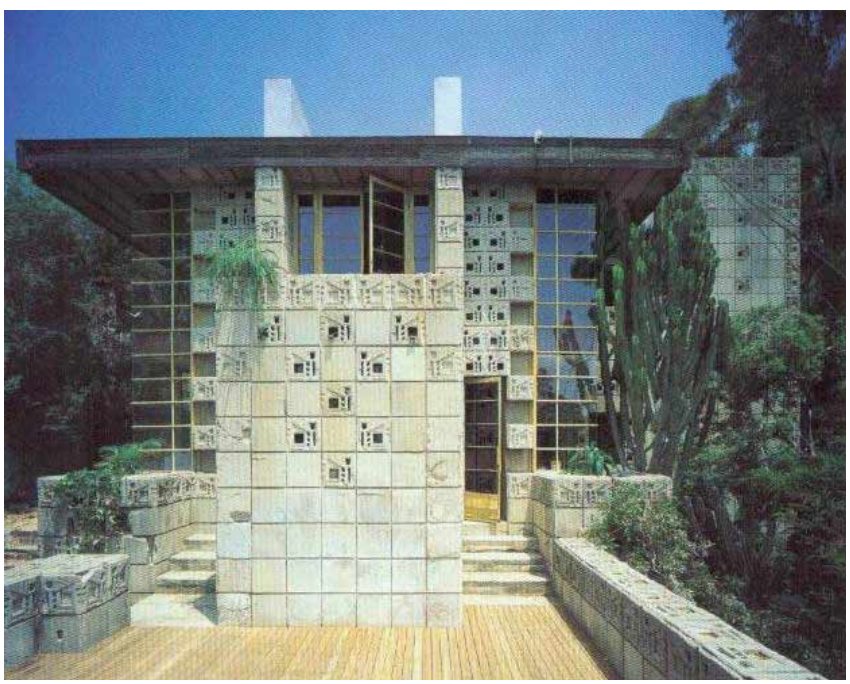

Figure 2: Freeman House west view

The existing structural system of the house in the east-west direction consists of textile bearing, and shear walls. In the garage area, concrete soil anchors are used to support basement wall. The existing structural system of the house in the north-south direction consists of two concrete portal frames to support the roof at the living room area. The textile walls are used as bearing wall and shear wall. Concrete soil anchors are used at north wall below grade. The slumber terrace consists of concrete soil anchors and textile walls.

The house was seriously damaged as a result of 1994 Northridge earthquake. Temporary shoring was provided to support areas that were most damaged. Extensive damages would be expected in a future seismic event. Repairs are made to restore structural integrity and provide life safety. These repairs are summarized as follows:

A. The two existing textile incased concrete portal frames were very lightly reinforced and clearly are not adequate to resist the code level earthquake. This required removing the existing textile blocks from the frame and reattaching them when the new concrete frames have been completed. It was an option to use these blocks as a form when building new frames. New textiles with the same appearance and color shall replace textiles damaged during removal process.

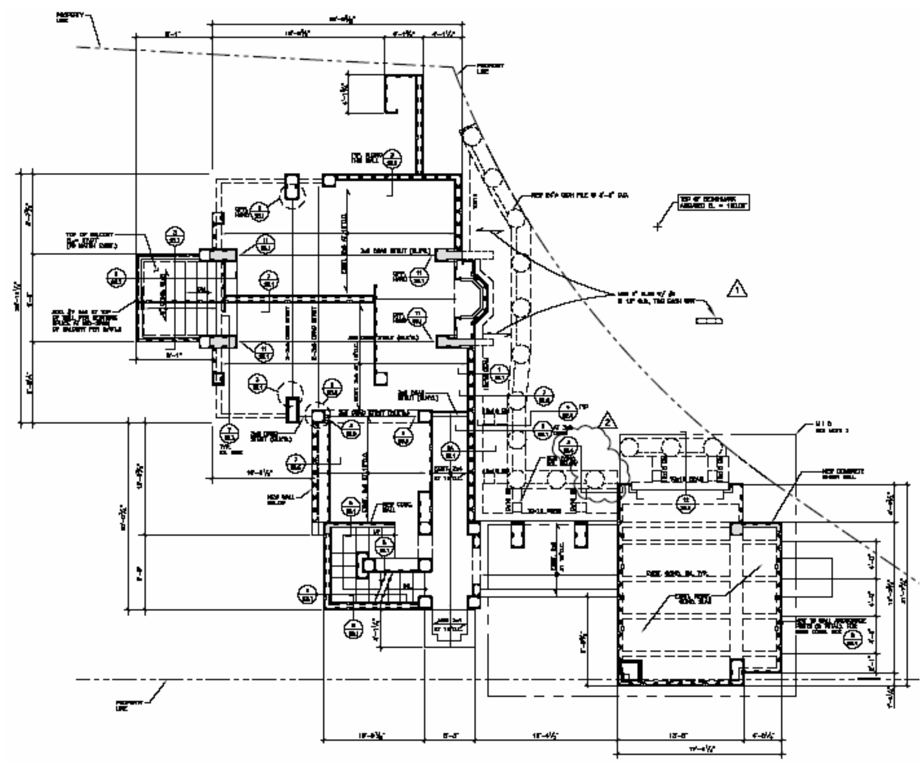

Figure 3: Freeman House plan view

B. North building wall below grade already showed signs of cracking and bulging at hall way, apartment area and garage area. In order to solve this problem, new retaining wall is added to north of building areas below grade. The retaining wall relieves the soil pressure from surcharging the textile wall.

C. A new concrete balcony and terrace will be built to form a buttress at south side of the building to prevent the building from further sliding and tilting. New textiles will be reattached with the same appearance and color.

D. Shoring is provided at southwest corner and southeast corner of the living room floor, due to access floor deflection and cracking at floor beam. New concrete frames at south façade repaired damaged living room floor beams.

E. Lack of adequate wall anchors has been noticed through out the building. To correct these deficiencies, positive wall anchors were provided at roof and floor level, by adding bond beams and anchor bolts positively tied to roof and floor joists.

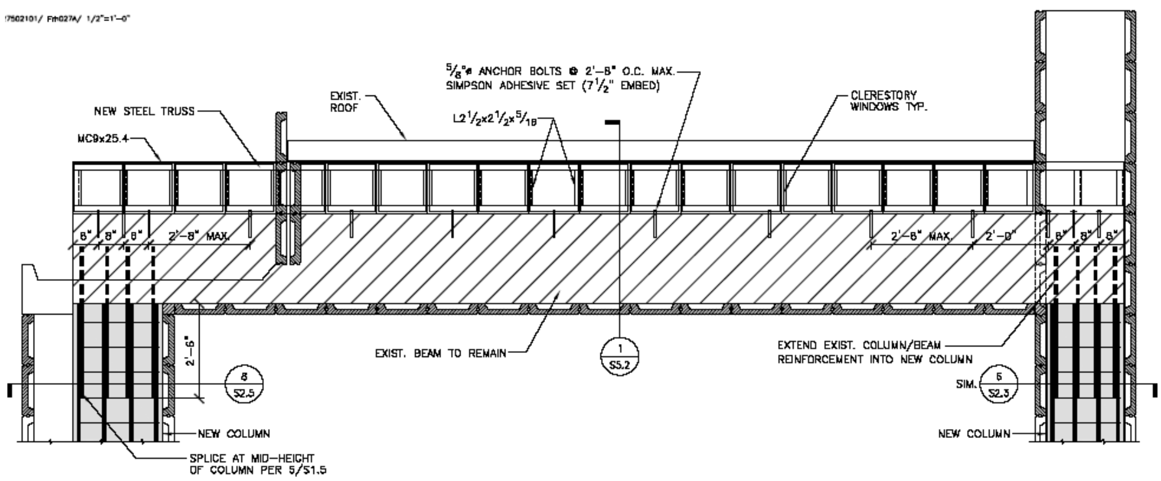

Figure 4: Strengthening concept for existing portal frame in Samuel Freeman House

F. Existing roof and floor straight sheathing were replaced with plywood structural diaphragm.

G. Removing south textile walls below kitchen floor, adding in new concrete shear wall, and replacing with new textiles with the same appearance.

H. The stair tower was not adequately anchored to the main house. This has caused the stair tower pulled slightly away from the main building. To repair this problem, positive anchors were used to tie the stair tower to building and interior stair supports were added.

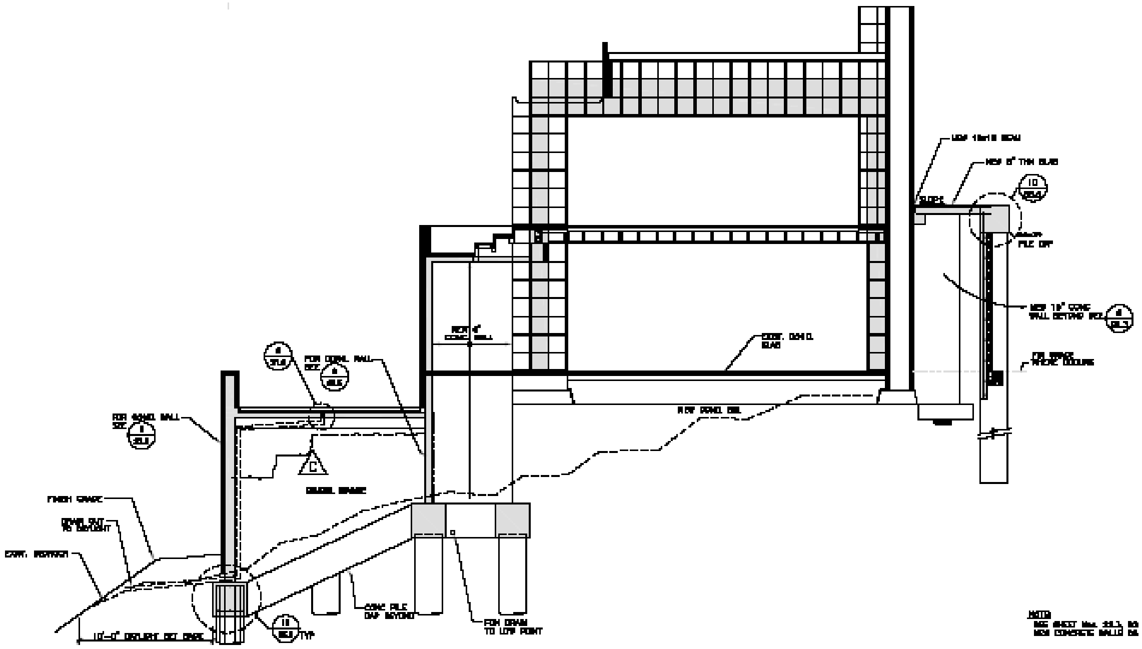

Figure 5: Section through Samuel Freeman House, showing new structural elements

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