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Seismic Strengthening Procedures for Existing Structures

Renforcement de structures existantes contre les séismes

Erdbeben - Sanierungsmassnahmen für bestehende Bauwerke

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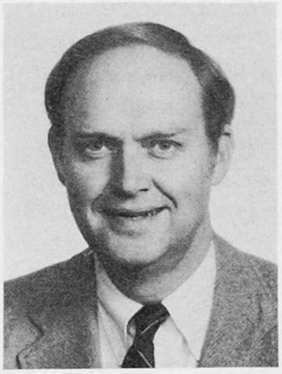

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SUMMARY

Seismic strengthening of existing structures is a common form of rehabilitation in areas of the world where earthquakes occur. Suitable criteria for each project must be established. The quality of the strength provided is usually more important than the amount of the strength since ductile performance of structural members is essential for sound seismic resistance. Schemes must provide balanced strength and stiffness throughout the structure without discontinuities. Several examples are included to illustrate current practice in the United States.

RESUME

Le renforcement de structures existantes contre les séismes est une forme de réhabilitation commune dans les régions du monde affectées par des tremblements de terre. Il est d'abord nécessaire d'établir des critères spécifiques pour tout projet donné. La qualité de la résistance ainsi apportée est généralement plus importante que la quantité proprement dite, car la résistance appropriée aux chocs séismiques dépend essentiellement de la ductilité des éléments structuraux. Tous les projets de renforcement séismiques doivent conduire à un équilibre entre résistance et rigidité sans aucune discontinuité dans la structure considérée. Plusieurs exemples illustrent ce qui se fait actuellement aux Etats-Unis.

ZUSAMMENFASSUNG

Die Verstärkung bestehender Bauwerke gegen Erdbebeneinwirkungen ist eine übliche Sanierungsform in Gebieten mit Erdbebengefahr. Für jedes Projekt müssen geeignete Kriterien erstellt werden. Die Qualität der Verstärkungen ist meist wichtiger als deren Ausmass, da die duktile Verformungsfähigkeit der einzelnen Bauteile für den Widerstand gegen Erdbebeneinwirkungen ausschlaggebend ist. Der Plan muss eine ausgeglichene und lückenlose Verstärkung der Gesamtstruktur vorsehen. Verschiedene Beispiele neuerer Methoden aus den Vereinigten Staaten werden aufgeführt.

1. INTRODUCTION

Seismic strengthening of existing structures is the judicious modification of the structural properties in order to improve the performance in future earthquakes. The strengthening can be performed after a damaging earthquake, in which case it is that work aimed at improving the structural performance beyond the actual repair of damaged members. Seismic strengthening can also be performed on undamaged structures in anticipation of future seismic activity.

The economical design of structures to perform adequately in strong seismic ground shaking requires a design criteria which anticipates that member yield capacities will be exceeded in strong ground shaking. This requires members to be proportioned and detailed for acceptable ductile performance. Simply sizing members for strength based on frame analysis calculations will not result in suitable performance in a severe earthquake. Ductility must be provided throughout a seismic resistant structure.

Strengthening a structure for improved seismic performance is similar to strengthening a structure for gravity or wind loads but the criteria and philosophy are different. The criteria must address the anticipated seismicity and ground shaking at the site of the structure. The philosophy requires a thorough evaluation of relative strength and stiffness throughout the structure and the quality or ductility of the strength for inelastic performance and then the prudent modification of strength and stiffness to achieve ductile, well distributed and balanced lateral force resistance. Modification of strength and stiffness generally involves increasing both, although in some structures stiffness of some elements may be reduced to strengthen the structure. The most critical task in seismic strengthening is realistically evaluating the ductility or the ability of the structure to perform in the inelastic range.

2. INVESTIGATION AND EVALUATION

A thorough investigation of the existing structure must first be performed to verify existing conditions and member proportions. Original construction drawings, specifications and calculations are invaluable reference documents when available. They must be verified with actual field conditions and all modifications or alterations must be recorded. Non-structural elements which can affect structural performance such as infilled partition walls or partial height masonry walls must be noted for an evaluation of their affect on structural response.

If the structure has been damaged in an earthquake, the damage must be thoroughly recorded. Notes and photographic record of each damaged member are necessary not only to design repairs but also to evaluate performance in order to design strengthening measures.

An evaluation must then be performed to estimate how the structure will perform in an earthquake. Calculations must be prepared to evaluate the building's strength for gravity and lateral loads, considering the relative rigidity of all elements including non-structural elements which affect structural performance. Of greatest importance is a qualitative evaluation of the inherent ductility or quality of the strength within the lateral force resisting system and a comparison of this type of construction to the historic record of performance of similar structures in past earthquakes. Experimental research incorporating seismic based cyclic load histories can also assist in the evaluation, but the actual details of construction seldom duplicate those of the laboratory research. This evaluation involves considerable professional judgment by a structural engineer who is knowledgeable how buildings actually perform in earthquakes.

If the building was damaged in an earthquake, the engineer must carefully study the damaged structure and thoroughly understand why the damage occurred. He must determine the force resistant paths in the building and explain the reasons why certain members sustained damage while other members were essentially undamaged. He must determine if the structure suffered due to discontinuities in strength or stiffness, due to torsional moments within the structure, due to hammering with adjacent structures or due to improper connections or details. He must consider the effects of non-structural elements such as infilled walls and appendages on the structural performance. He must determine if members failed due to shear, compression, flexure, bar anchorage, etc. This study and understanding of the seismic performance generates essential input for developing a suitable strengthening solution.

The decision to intervene or to strengthen the structure is based on this evaluation. It generally follows that the key factor governing the decision is the ductility or lack of ductility in the existing structure. For example, if the structure consists of reinforced concrete frames not specifically detailed for ductility for seismic forces and without shear walls, strengthening is appropriate as buildings of this type have historically exhibited poor performance and lack ductility.

3. CRITERIA FOR STRENGTHENING

Criteria for seismic strengthening projects can be simple or complex. The criteria selected must be suitable to accomplish the goal of the strengthening. The goal of the strengthening may be to comply with current Building Codes or Regulations because of an increased occupancy or retroactive compliance requirement; to voluntarily strengthen a weak-link in the structure; or to improve the overall seismic resistant performance, either to prevent potential structural collapse thereby protecting occupants or to minimize damage thereby protecting financial investment as well as occupants.

If the goal is to comply with Building Codes or Regulations, then those Codes or Regulations generally become the criteria, unless the engineer feels that a more severe criteria is appropriate and the owner agrees. If an evaluation of the existing building reveals that it has a "weak-link", such as a discontinuous shear wall, and it is decided to strengthen the building only to eliminate the "weak-link", then the lateral force design level consistent with the original design may form suitable criteria. If the goal is to strengthen the building voluntarily beyond regulations, then the engineer should select appropriate criteria. That criteria may be the current Building Code, an older edition of a Building Code with a lower lateral force design level combined with current code ductility requirements, or a criteria developed for the site based on soil conditions, and local and regional seismology. Regardless of which criteria is selected for design, the criteria must include requirements for adequate ductility in the structural members and their connections or joints.

4. DEVELOPMENT AND SELECTION OF STRENGTHENING SCHEMES

Once the decision to strengthen the building is reached, the engineer must conceive numerous different ways the building can be strengthened. These methods include adding reinforced concrete or masonry shear walls, adding structural steel diagonal bracing or new frames, adding reinforced concrete jackets to increase ductility and strength of concrete frames, adding reinforced infilled wall panels, or other suitable methods. Strengthening a building for seismic forces generally involves increasing its stiffness, although some strengthening solutions may involve the reverse when selected columns are short and stiff or other unbalances existing in the stiffness and strength of framing members. The strengthening solutions must be compatible with the functional usage of the building which will strongly influence the solution selected.

The proposed strengthening schemes must correct the observed or anticipated weak links in the lateral force resisting system. The schemes should provide uniform strength and stiffness distributions both over the height of the structure as well as throughout its plan. The effects of non-structural elements should be considered and controlled either by isolation from the structural members or incorporation into the lateral force resisting system. Diaphragm strength and stiffness should be verified to assure that lateral forces can be properly distributed to new bracing elements, and new collectors, struts or ties added as appropriate. Of prime concern is insuring adequate ductility in the structure. Imagination and ingenuity should be exercised by the engineer while utilizing his professional experience in structural performance and construction techniques.

The alternative schemes need to be compared and their advantages and disadvantages weighed in order to select a preferred scheme. Items to be considered in this comparison include compatibility of the solution with the functional requirements of the building, feasibility of construction including availability of materials and experienced workmen, economical considerations, aesthetics and sociological considerations. Obviously, all schemes must comply with governmental regulations and the goals and criteria which were selected.

The selected solution for strengthening must then be thoroughly developed with all details established and clarified. The engineer must perform calculations and analysis to establish which members will sustain initial inelastic response as such response in columns may jeopardize the vertical support of gravity loads. The effects of added strengthening elements must be carefully evaluated to insure that they will not cause increased damage in future earthquakes. For example, frame buildings have been damaged in their first story in an earthquake and strengthened only in that story. The next earthquake has left the stiffened first story essentially undamaged but caused extensive damage in the unstrengthened upper floors. Such response should be anticipated and controlled within the initial strengthening program.

5. CONSTRUCTION EXECUTION

The drawings and specifications for seismic strengthening must be precise and detailed as strengthening elements will not function properly if all connections are not built in response to design requirements. This need is compounded as in all building strengthening projects as exact "as-built" conditions are not always accurately known until exposure during the construction work. Thus, it is frequently necessary to prepare details based on the best knowledge available and then modify them during construction when actual conditions are determined.

Due to this need to constantly monitor existing conditions as exposed and modify details to suit these "as-built" conditions, it is essential for strengthening projects that the design engineer be involved in the construction inspection process. The designer must periodically visit the structure during construction both to view exposed conditions for damage or distress as well as observe conditions to insure compliance of the construction work with the intent and assumptions of the design.

Strengthening projects also involve the use of new or seldom used construction materials and techniques which require precise specifications and instructions to the workmen as well as carefully conceived inspection procedures to insure that the construction work complies with the design intent. Many procedures involve fastening new materials to old existing materials with the quality of workmanship being a major factor affecting strength and performance. Thus, extensive field testing of connectors and fastenings is essential for a successful project.

6. EXAMPLES

6.1 Example No. 1

The existing building is a three-story reinforced concrete structure 58 meters square in plan, as shown in Figure 1. It is an office building. The First Floor is a slab on grade while the upper two floors are a concrete waffle slab

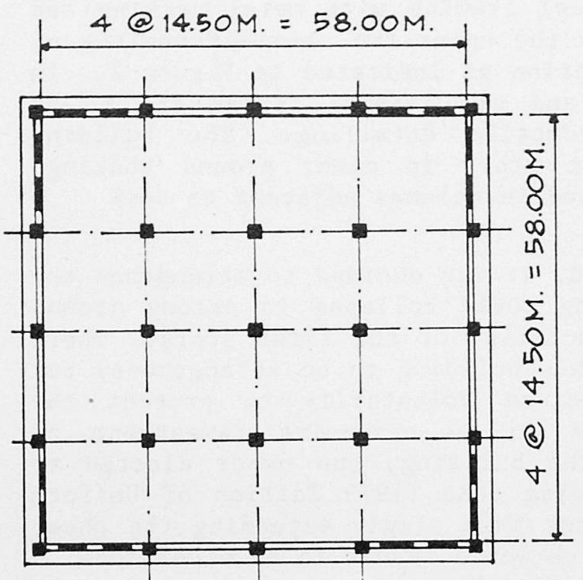


Figure 1. Typical plan of three-story Office Building in Example 1. Walls present only in upper two stories.

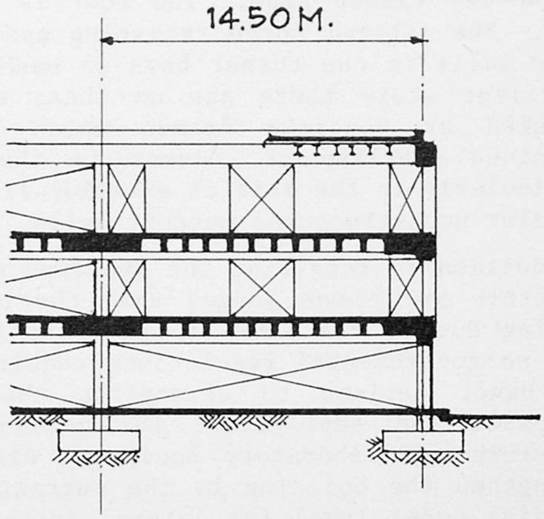


Figure 2. Partial elevation of exterior frame showing extent of existing walls in Example 1.

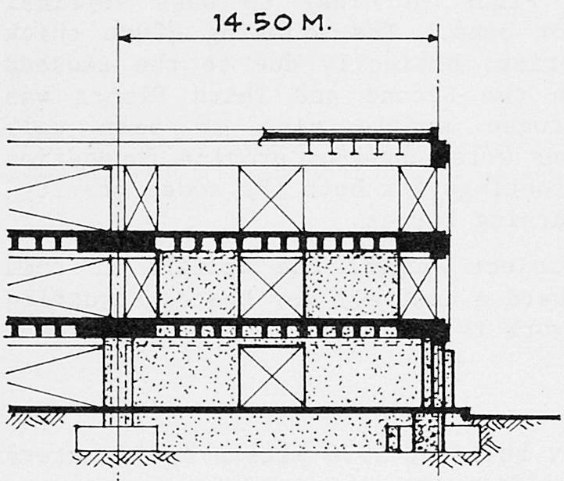


Figure 3. Partial elevation of strengthened wall system in Example 1.

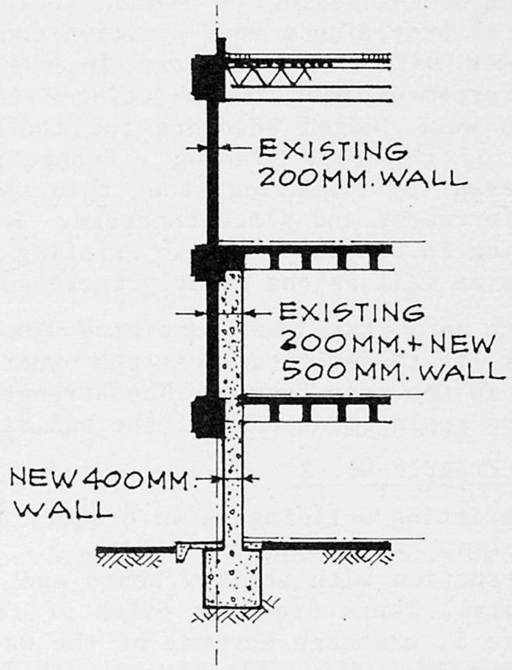


Figure 4. Section through strengthened wall in Example 1.

or two-way ribbed slab. The roof is of steel framing with metal decking and fill. The lateral force resisting system in the upper two stories consists of shear walls in the corner bays on each elevation as indicated in Figure 2. In the first story there are no shear walls and all lateral forces are to be resisted by concrete frames which lack ductile detailing. The building sustained spalling of columns in the first story in minor ground shaking, particularly in the stiffer exterior frames and in columns adjacent to some interior non-structural masonry walls.

In addition to repairing the observed damaged, it was decided to strengthen the structure as it was judged that the building could collapse in strong ground shaking due to the lack of stiffness and ductility of the first story. There were no governmental regulations requiring this building to be strengthened but the owner decided to strengthen the structure voluntarily to protect the occupants and employees. Furthermore, due to an extensive investment of computers and laboratory equipment within the building, the owner elected to strengthen the building to the current building code (1979 Edition of Uniform Building Code) level for lateral forces rather than simply extending the shear walls in the upper stories to the ground (which would result in an older code with lower lateral forces being the design criteria).

The strengthening solution is outlined in Figures 3 and 4. Shear walls 400mm thick were added in the First Floor beneath the existing 200mm thick shear walls in the upper stories. These walls were extended upward in the Second Floor by adding a thickening of 500mm, thereby both strengthening the Second Floor as well as providing a very positive connection between the new and old walls. The thicker wall was necessary in the Second Floor in order to pass vertical reinforcement past the existing Second Floor beam. The existing 200mm thick walls were judged adequate for the top stories, basically due to the reduced mass of the roof framing. Connection with the Second and Third Floors was achieved by removing the thin slab between waffle ribs to pass wall reinforcement and place concrete. Foundations were added to provide foundation bearing in conjunction with existing spread footings for both the added gravity loads as well as the greatly increased overturning forces.

Design work has been completed for this project and at the writing of this paper, it is estimated that the owner will award a contract for the construction work in the near future. The strengthening work is estimated to cost about 8% of the replacement cost of the building.

6.2 Example No. 2

The existing building is an 8-story dormitory building 57.6 meters by 17 meters in plan, as shown in Figure 5. The building is of reinforced concrete construction with shallow beams and slabs which are not shown in Figure 5 for clarity. There are four pairs of reinforced concrete shear walls as shown in Figure 5, although several of the walls are discontinuous in the Ground Floor. The two long sides are framed with 600mm square columns and beams or spandrels of reinforced concrete 2000mm deep extending from the window head in one story to the window sill in the story above. The columns are tied columns with ties at 450mm centers. The building has not been subjected to strong ground shaking but the owner has requested an evaluation of its potential seismic performance and recommendations for mitigation measures if appropriate.

The evaluation revealed that the building has sufficient shear walls in the north-south direction to adequately brace the building in that direction, but the discontinuous shear walls in the Ground Floor result in overturning forces being resisted by nominally tied columns which have traditionally exhibited a lack of ductility in earthquakes. In the east-west or longitudinal direction, the two exterior frames resist virtually all of the lateral forces due to their stiffness, and the deep spandrel beams are stronger than the columns which will force the inevitable inelastic response into columns. The nominally tied columns have virtually no ductility and their potential inelastic response will

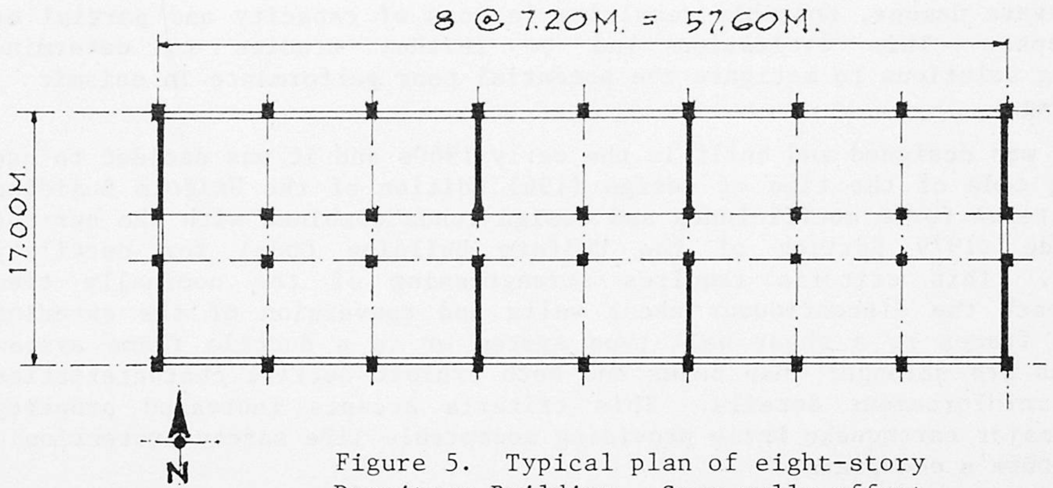


Figure 5. Typical plan of eight-story Dormitory Building. Some walls offset in Ground Floor.

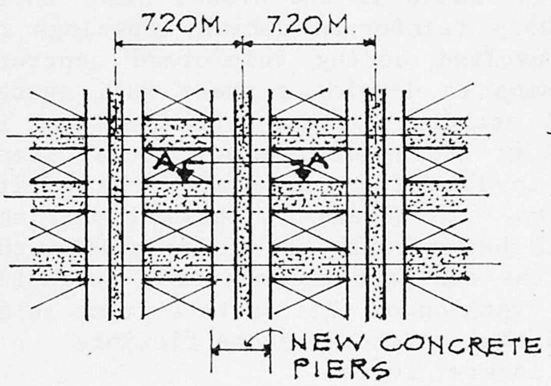


Figure 6. Scheme A strengthening adding concrete piers to existing columns to create shear wall bracing system on side walls.

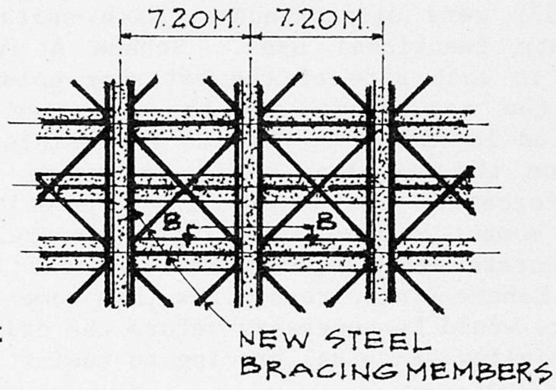
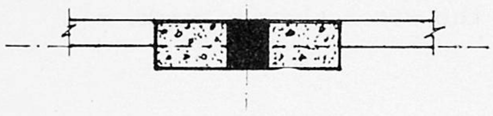
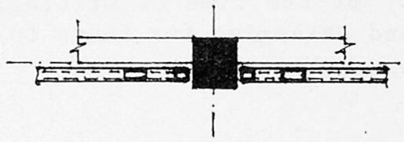


Figure 7. Scheme B strengthening adding steel bracing to existing frame on side walls.



Section A-A in Figure 6.



Section B-B in Figure 7.

result in severe damage, possibly resulting in loss of capacity and partial or total collapse. This evaluation led to further studies to determine strengthening solutions to mitigate the potential poor performance in seismic ground shaking.

The building was designed and built in the early 1960s and it was decided to use the building code of the time of design (1961 Edition of the Uniform Building Code) for lateral force coefficients and design loads combined with the current building code (1979 Edition of the Uniform Building Code) for ductility requirements. This criteria requires strengthening of the nominally tied columns beneath the discontinuous shear walls and conversion of the exterior longitudinal frames to a shear wall type system or to a ductile frame system where columns are stronger than beams and both exhibit ductile characteristics from their reinforcement details. This criteria accepts increased property damage in a major earthquake while providing acceptable life safety protection to the structure's occupants.

Many alternative solutions of strengthening were studied, and two basic solutions were presented to the owner for consideration. Both solutions included adding new reinforced concrete shear walls in the Ground Floor where shear walls were discontinuous, with suitably reinforced doorway openings to accommodate functional uses. Scheme A involved adding reinforced concrete sections to each side of the exterior columns to develop a shear wall system between the new piers and the existing spandrel beams. This scheme is illustrated in Figure 6. Scheme B consists of adding exposed structural steel bracing on the two long sides, as shown in Figure 7, to resist the entire lateral forces in the longitudinal direction. In Scheme B, the existing top negative moment reinforcing in the spandrel beams would be cut to weaken the stiff concrete exterior frame and protect the concrete columns from extensive damage. Scheme B also recognizes that some cracking of the concrete frame in an earthquake would be necessary before the existing concrete become flexible enough to allow the steel bracing to resist lateral forces.

Scheme A requires partial vacating of the building to allow work to proceed and results in a loss of windows for natural light. This scheme is probably more pleasant aesthetically and is estimated to cost about 35% of the building's replacement cost. Scheme B allows most of the work to be performed on the outside of the building without vacating the building except portions of the Ground Floor for the shear wall work. The exposed steel frame does not result in a loss of windows. Scheme B is estimated to cost about 25% of the building's replacement cost. At the time of writing, the owner is studying the merits of the two schemes and arranging for funds to finance the strengthening work.