13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2283

STRENGTHENING OF EXISTING BUILDINGS AGAINST EARTHQUAKE WITH CONSIDERATION OF ECONOMIC CONSTRAINTS IN DEVELOPING COUNTRIES

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SUMMARY

Developing countries located in earthquake prone areas of the world can anticipate huge life and property loss during major earthquakes. The study that was recently conducted for the city of Tehran indicates that the economic loss due to a scenario earthquake with intensity IX (MMI) will amount to tens of billion US dollars, not mentioning the loss of many lives and the chaos following the event. Obviously such loss may exceed the GNP of the nation. There are many old buildings of various types in Iran that have the potential for strengthening to withstand earthquakes with lower Intensity, say VI or VII (MMI). For developing or poor nations it would be unreasonable and economically unfeasible to demolish old buildings that do not meet the requirements of their respective seismic codes. This is a luxury that developing countries cannot afford. Building strengthening should be gradual process in order to be acceptable to their owners and the authorities and at the same time feasible to implement. One philosophy that may be adopted for developing countries is to survey, identify and categorize the buildings based on their inherent lateral load resistance levels. The strengthening can be a gradual process and therefore be planned for different levels of earthquake intensity. Therefore, the extent of damage during earthquakes of different intensities can be controlled without imposing sudden major economic impact on the nations. The survey of several hundred buildings of different structural types and usage was carried out for the entire city of Tehran recently. Earthquake resistance level for those buildings was determined. Based on the above philosophy and the knowledge gained about the existing buildings, several levels of appropriate strengthening methods were established. This paper presents the established strengthening methods and their respective cost savings for different levels of earthquake intensity, compared with full-fledged strengthening complying with the code requirements.

INTRODUCTION

In developing countries the labor cost is low but the material is relatively expensive. The opposite is true in developed countries. Therefore, The building strengthening solutions should consider use of more labor and less material (preferably locally produced ones). If the strengthening details are made simple and labors are properly trained for strengthening then, time, material and cost saving can be achieved.

Microzoning of a city is effective in developing reasonable Acceleration Response Spectrum of ground surface in each zone, for which strengthening of buildings is targeted. In developed countries where detailed and numerous records of past earthquakes and respective damage to the buildings are available, Fragility Function provides a relationship between building damage and ground motion for the scenario earthquake.

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In developing countries the earthquake records are mostly limited to recent time and there is a general, but not detailed, knowledge of the corresponding building damage. It would be more reasonable to diagnose the building types, identify their weak links and then study their capacities according to the scenario earthquake input motion and the country's earthquake code. Based on this evaluation one can propose the suitable strengthening method. Based on the importance of buildings and the available budget the strengthening should be a gradual process and be done using the ground motion information related to each location.

PHILOSOPHY

The philosophy of all codes is to maintain life safety of the inhabitants during earthquake. However, the building damage may be tolerated to some degree. For developing countries it may not be economically feasible to fully comply with the earthquake codes and design or retrofit the existing buildings for non-frequent earthquakes. One idea is to apply the microzoning concept and determine the anticipated ground motion at those zones based on the higher probability of occurrence, say 50 years. Using such scenario earthquake and also obtaining knowledge on the condition of building (aging, deterioration, design flaws, construction quality, etc.), one can present strengthening methods that would be more affordable for developing countries.

The study on seismic microzoning of the Greater Tehran Area was conducted by the cooperation of Japan International Cooperation Agency (JICA) and Center for Earthquake Studies of Tehran (CEST) during a period of 18 months (1999-2000). Figure 1 shows an example of scenario earthquake based on the Ray Fault Model and the expected earthquake intensity in different districts. It can be seen that lower intensity is to be expected in northern districts.

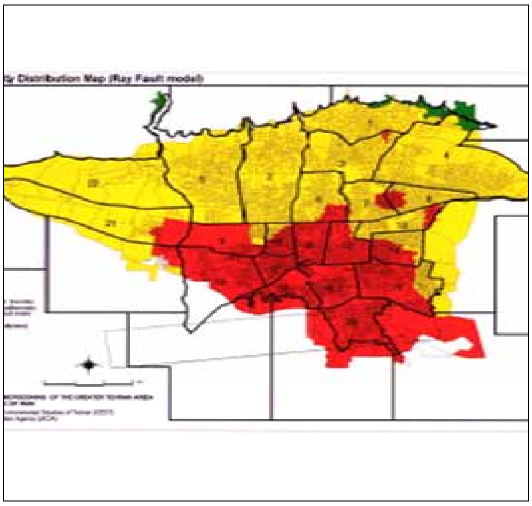

Figure 1- Seismic Intensity distribution map of Tehran based on the Ray Fault Model

Many buildings in 22 districts of Tehran were also inspected. The evaluation of surveyed buildings, by the Japanese Building Evaluation System, is based on defining seismic index or so–called **GIs** as briefly described below.

$$GIs = Q_u / \alpha \,.\, Q_{un}$$

Where,
GIs: seismic index
Q_u: seismic force level for ultimate capacity check
α: correction coefficient (to account for aging deteriorations defects, etc.) as defined in Japanese Guidelines
Q_{un}: Required seismic force level for ultimate ductility check (base shear force), or required building

capacity

Hardly any building in Tehran meet the demand expected by “GIs”. The reason is the difference between the codes, design, material quality, method and the quality of construction in Iran compared to Japan. To lax the GIs demand, the Iranian seismic code (Standard 2800), [1] was utilized. Even with the lower response spectrum of Iranian code the buildings proved inadequate Figure 2.

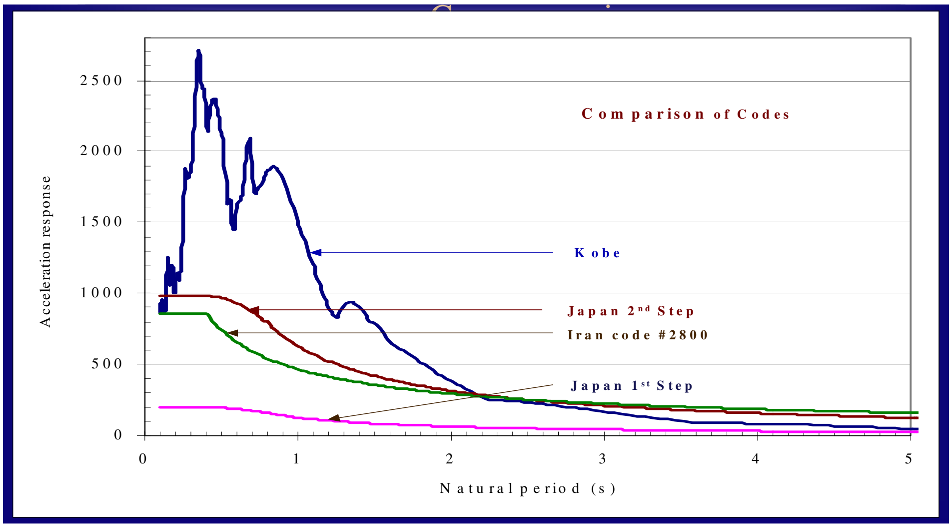

Figure 2- Comparison of codes and Kobe earthquake Response Spectra

This finding implied that many buildings in Tehran have to be rebuilt or strengthened at a prohibitive cost to the nation. Therefore, further consideration to lax the demand on existing buildings on a logical basis is necessary. That is why the use of lower response spectrum based on Microzoning the city seems appealing, while similar index as GIs discussed above can be employed with the emphasis on using less stringent values for correction factor term, α, in the Japanese guidelines. The quality of material and method of building construction is discussed next to explain some of the reasons for low building earthquake resistance capacity in the existing buildings of Tehran.

GENERAL OBSERVATION

Buildings’ dead weights are heavy. There are unnecessary heavy loads imposed by the walls and floors and their material density is very high, for example:

- There are thick walls and floors, which also do not necessarily provide proper thermal insulating properties such as solid brick covered with thick layer of clay mixed with gypsum, and gypsum finish at interior, and thick layer of grout plus stone or brick for veneer.
- Typical floor of jack arch brick, or joist and block floors are heavy, with dead weight of 540-600 kg/m^2. A relatively significant portion of dead weight is due using a layer of volcanic ash on the floor. This layer is used throughout the floor areas just to provide adequate thickness for the passage of piping and electrical conduits.
- The majority of steel joists are not tied together and do not provide diaphragm action. The infill walls and parapets are not tied to the structural framing system, thus there is no safeguard against their movement during an earthquake.
- Using untrained laborers such as steel or concrete workers had resulted in many defects in the workmanship.
- Lack of proper and frequent supervision by experienced and qualified engineers has left most of the workmanship defects in place.

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Workmanship
Closely related to detailing of a building's design and construction is the quality of construction. Numerous collapses or other sever damages in the recent Bam earthquake, even in newly constructed buildings were due to poor workmanship. The problems were brittle and sudden breakage of joints or buckling of bracing members, which were poorly welded. Tehran steel buildings also use similar details. The problem is mostly attributed to lack of skilled and knowledgeable labors and even building inspectors or construction supervisors.

Building walls and veneers
Masonry veneer that is an appealing architectural feature by owners is very common in Iran. Masonry veneer of brick or stone usually on outside walls are attached to the surface of brick or lightweight concrete block walls. The walls are either load bearing (masonry buildings) or non-load bearing .the non-load bearing infill walls are placed within the structural framing without ties (concrete or steel). The veneers doe not support any load from the building and are not specifically designed and reinforced for earthquake forces. With lack of proper connecting ties the infill walls or parapets separate themselves from the building's framing during earthquake. Many such cases were observed in the past earthquakes and recently in Bam. The detachment was more common in upper stories.
Poor quality mortar such as lime-sand in masonry buildings even lime and clay are used as veneer mortar for bricks. Added to this dilemma is the lack of vertical grout between brick veneers.

The common practice to install stone veneers is to hold the stone and place 3-5 cm of sand-cement grout between them. After few years of exposure to seasonal temperature fluctuations the stones detach themselves from the existing walls and fall down. To remedy this the owners drill holes in stone and the back mortar and roll plug them. Recently, they make cuts along the 4 edges of stone, place a regular reinforcing tie wire in the form of X behind the stone, which is passed through the cuts. The wire is then imbedded within the back grout. In the Bam earthquake all of these methods failed. Stones or wires were broken and they fell down to the streets.

Observation on the construction techniques
The old buildings are URM and are not engineered. Their construction is purely traditional and all lack drawings and use brick with low quality mortar. The numbers of stories are up to 4, excluding basement. The builders of old URM buildings were the owners themselves who had hired the so-called Master Masons and untrained labors. These buildings have no inherent earthquake resistance capacity. The cost of strengthening them would probably reach up to 50 percent of the building's value. As part of seismic code requirements masonry buildings started using horizontal ties and later combination of horizontal and vertical ties. The code limits the number of stories to 2. They performed well in the past earthquakes.

Architects designed relatively newer URM's, with emphasis on providing large uninterrupted interior space and comfort and esthetically appearing facade. The architect specified the beam and column sizes using rule of thumb. There are many charming villas and apartments, up to 5 stories, of these types throughout Tehran. Contrary to old URM's this generation of building have less bearing walls inside and the floor loads are supported by partial frame comprising of few simple supported girders connected to small number of columns, by the so-called "khorjini" framing or connection. There are only architectural drawings for the latter building types. The URM's with partial khorjini frame posses some degree of earthquake resistance. Due to ease of access to framing their strengthening is feasible. There are few test reports on their behavior and degree of joint rigidity, Tahooni [2].

With the introduction of seismic code, the construction of engineered buildings using full beam-to-column steel framing started. Initially the framing started with khorjini connection framing and later changed to full beam-column framing similar to the ones used in developed countries.

High strength steel profile or wide flange sections (H sections, etc.) are used for special projects. But they are imported. For typical buildings it is customary to use locally produced profiles. The steel is almost all of St-37 type. The locally manufactured profile types and the sizes are limited, hence by combining IPE, I, [or oven L sections Latticed Columns are formed. In recent years, the use of box columns became popular. They ore manufactured by using plate or covering single or double I section's periphery by plate(s).

The beams are usually castellated, one member for joists and two, side by side, I sections for main girders. The detail of beam-to-column attachment is usually hinged and the framing relies on bracing to resist lateral loads. Judging from the workmanship most details have brittle fillet welds. Bracing with many standard or non standard configurations such as single or double L, or I profiles are used.

Practically in all steel framings the beam-to-column connection, even in most of the so called moment resisting frames, are fillet weld with poor workmanship (poor or inadequate welding). The construction is done at site therefore, groove forming or welding is costly and not much practiced.

The old RC buildings are regular framing with non-ductile connection and almost all lack shear wall. They have used plain reinforcement with inadequate stirrups. This trend continued until seismic code, demanding ductile beam-to-column connection, was introduced.

The floors of all buildings are jack arch, joist and block and recently composite construction. In old buildings the floor joists are not tied. The use of soft story in all types of buildings is very common and has been the cause of many failures.

Similar observations may be seen in other developing countries. Therefore, the building design and construction culture do not necessarily comply with the design and workmanship as practiced in the developed countries and for their strengthening solutions one should not necessarily use their practice.

LEVELS OF STRENGTHENING

Based on the results of building investigation in each Microzone, budget constraint and emphasis on life safety, one may consider different types and levels of strengthening. They are listed by the order of difficulty and cost as follows:

1- Secure parapets, infill walls and veneers to the framing using ties.
2- Reduce excess dead weight of the structure by replacing existing heavy material and substituting lighter weight ones.
3- Strengthen the connections
4- Add bracing
5- Strengthen the framing members or add new structural members or ties in URM buildings.
6- Add shear walls.
7- In all cases check the foundation and strengthen, if necessary.

Reducing existing buildings' dead weight in developing countries is very rewarding as it utilizes low cost labor and at times this action alone may eliminate or reduce the need or level of strengthening. If the existing dead weight is maintained and strengthening is done in the members' joints or by adding shear walls, shorter structural period may result and hence larger inertia force may be imposed on structure.

When considering strengthening in developing countries, it is worth noting that providing proper ductility may not be as simple as providing force capacity (Figure 3). More precision work and attention to detailing is needed, which may not be obtained due to lack of specialized labor or difficulty to have access to the joints. For instance, it is a lot easier to install bracing or add shear wall to the existing building than having to obtain access to a hinged joint and try to convert it from simple fillet welded connection to a ductile connection with groove welding. Furthermore, additional members have to be attached to column in order to provide panel zone, provided that column design would allow this. Also difficulty of access or lack of working space may not allow this. Some of the following sophisticated solutions may not be economical for small residential or office buildings:

a- Active control
b- Use of carbon fiber
c- Unbonded brace
d- Viscous brace (brace with viscous material inside)
e- Energy dissipation
f- Elasto-plastic high ductility material
g- Shear wall with energy dissipation effect (sandwich)
h- Base isolation (high damping rubber, lead core rubber bearing)
i- Lead extrusion damper
j- Friction and pendulum

The above means require purchase of imported parts at substantial cost. Furthermore, the technology and skilled labor, for their installation, may also have to be imported. The use of the above strengthening methods could be justified for the governmental, hospitals, historical buildings or new mid to high rise buildings. Among the above methods items g and h have more potential to be manufactured and implemented in developing countries.

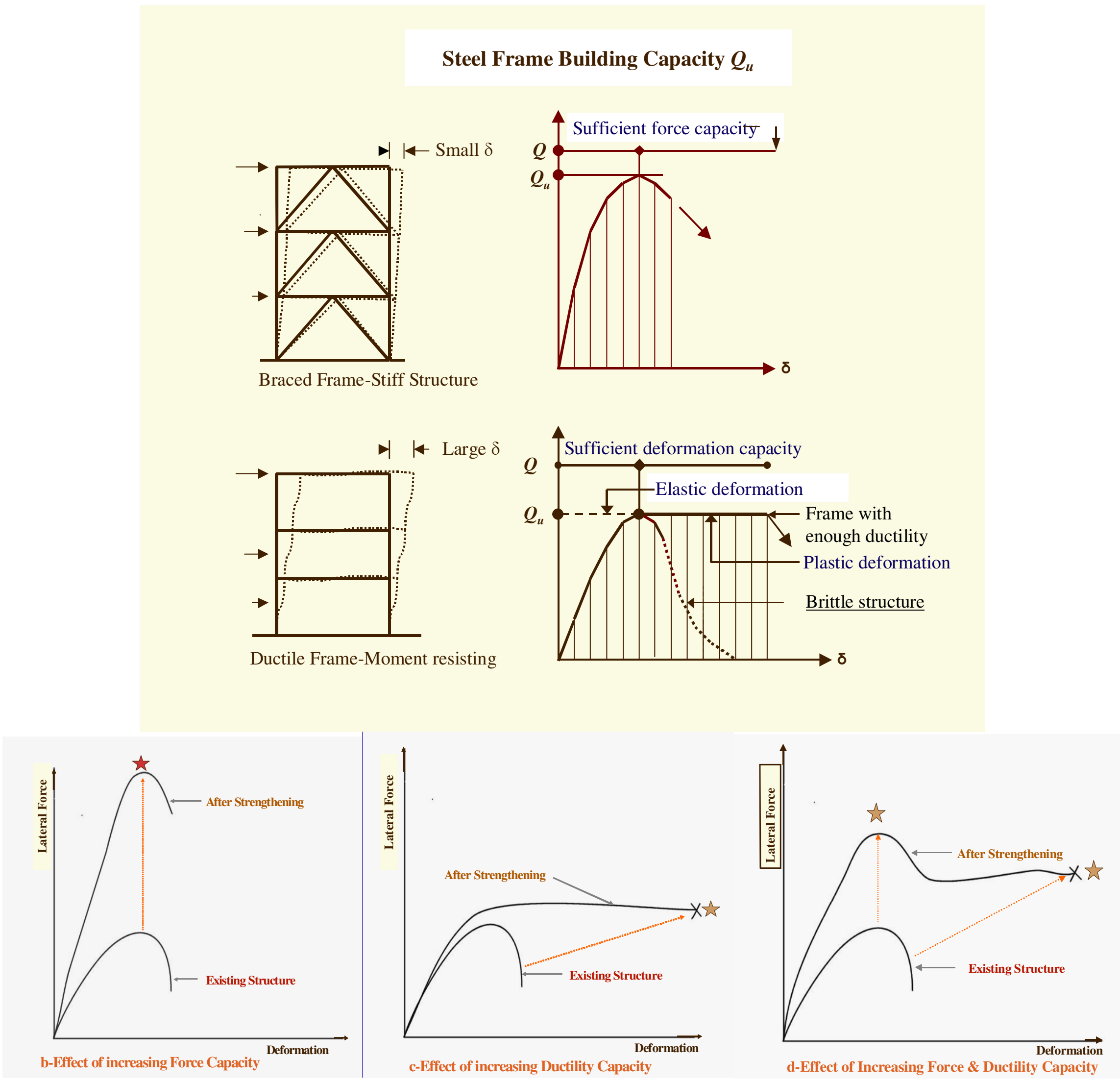
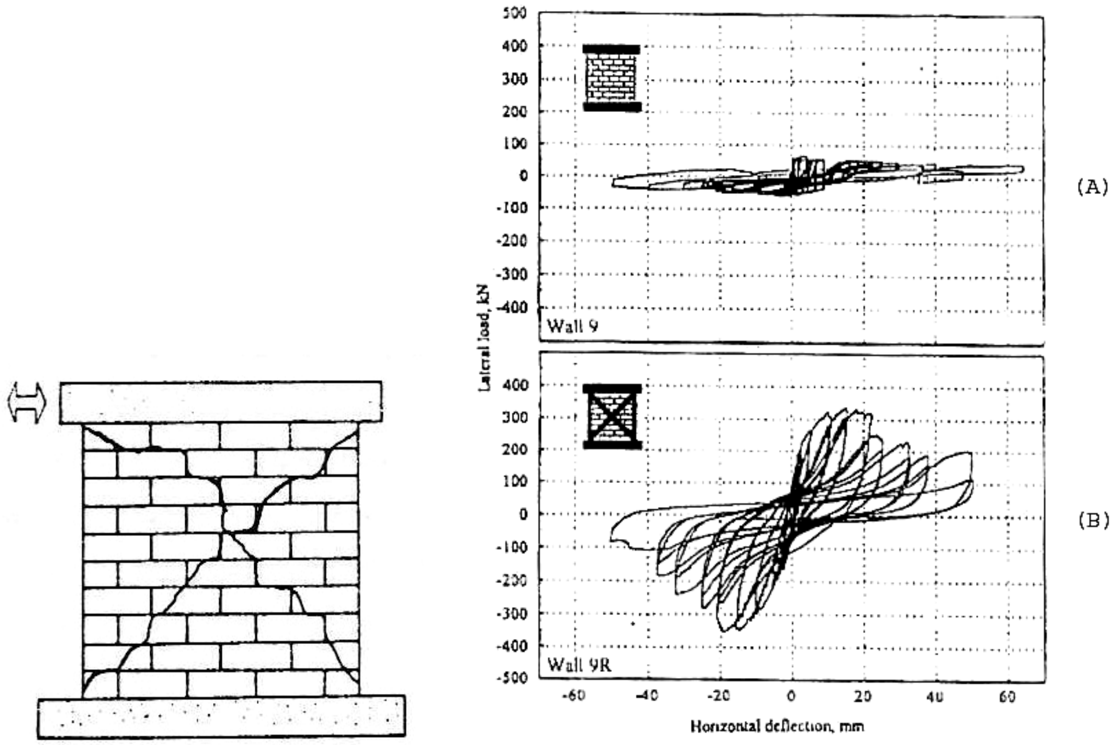


Figure 3- Effect of increasing building lateral resistance capacity

There are several world wide experimented results that may be used as a guide to optimize the strategy for strengthening. They use simple standard building material and thus more practical for developing countries. Figures 4 and 5 show some simple and effective means of strengthening by increasing the existing building's force resistance capacity.

As explained in the introduction the relative cost of labor to material are opposite of that in the developed countries. Therefore, the strengthening details that utilize more labor and less material may be more economical solutions for the former case. Also, due to the non-ductile connection of most existing building framing, the strengthening concept should be based on increasing buildings force resistance capacity, rather than increasing the deformation capacity.

One advantage of solutions in Figures 4 through 6 is the use of standard equipment, material and technology. Obviously the labors should be properly trained to increase their efficiency for installing seismic components such as dowels or connectors for tying the new and existing parts.



Shear Failure of Brick Wall due to Innerplate Lateral Force

A) Hysteresis Loop of Unreinforced Brick Wall
B) Hysteresis Loop of Brick Wall Reinforced by Steel Strips

Figure 4- Behavior of masonry wall and effect of strengthening by adding bracing

Weight Reductions and Improving Quality of Masonry and Lowering Unit Construction Cost
Existing building, using year 2002 Exchange Rates:

Solid brick wall 11cm thick with 3 cm clay + gypsum and 1 cm gypsum finish sides, 310 kg/m^2,
Cost: ≈ 10 USD/m^2

New solutions:
- Dry wall, 12.5 to 15 cm thick, 40-50 kg/m^2, cost: ≈ 12.5 USD/m^2
- Wall with Foam Concrete block with a 1 cm thick layer of gypsum on both surfaces 70-85 kg/m^2, cost: ≈ 10 USD/m^2

Floor Weight and Unit Construction Cost
Existing buildings:
Jack arch ≈ 500 kg/m^2, cost ≈ 14 USD/m^2. On existing jack arch one may consider removing top excess dead weight and place a thin layer of lightweight concrete. Also attach floor bracing.

Joist and block + 6 cm volcanic ash + tile and grout + 2 cm clay and gypsum+ 1 cm gypsum finish ≈ 600 kg/m^2, cost ≈ 14 USD/m^2.

New construction:
- Composite construction with lightweight concrete ≈ 280 kg/m^2, cost ≈ 13 USD/m^2

Strengthening Masonry Buildings

The new buildings mainly use hollow brick, which are substantially lighter than solid brick (850 kg/m^3 compared to 1850 kg/m^3 for solid brick).

The hysteresis loop of URM buildings shows very little energy absorption capability during earthquake, Tasnimi [3]. They are very brittle and failure takes place at the initial cycles of deformation. Adding steel or concrete ties, bracing or shear walls, or even use of Base Isolation System (BIS) would greatly improve this shortcoming (Figures 4 through 6).

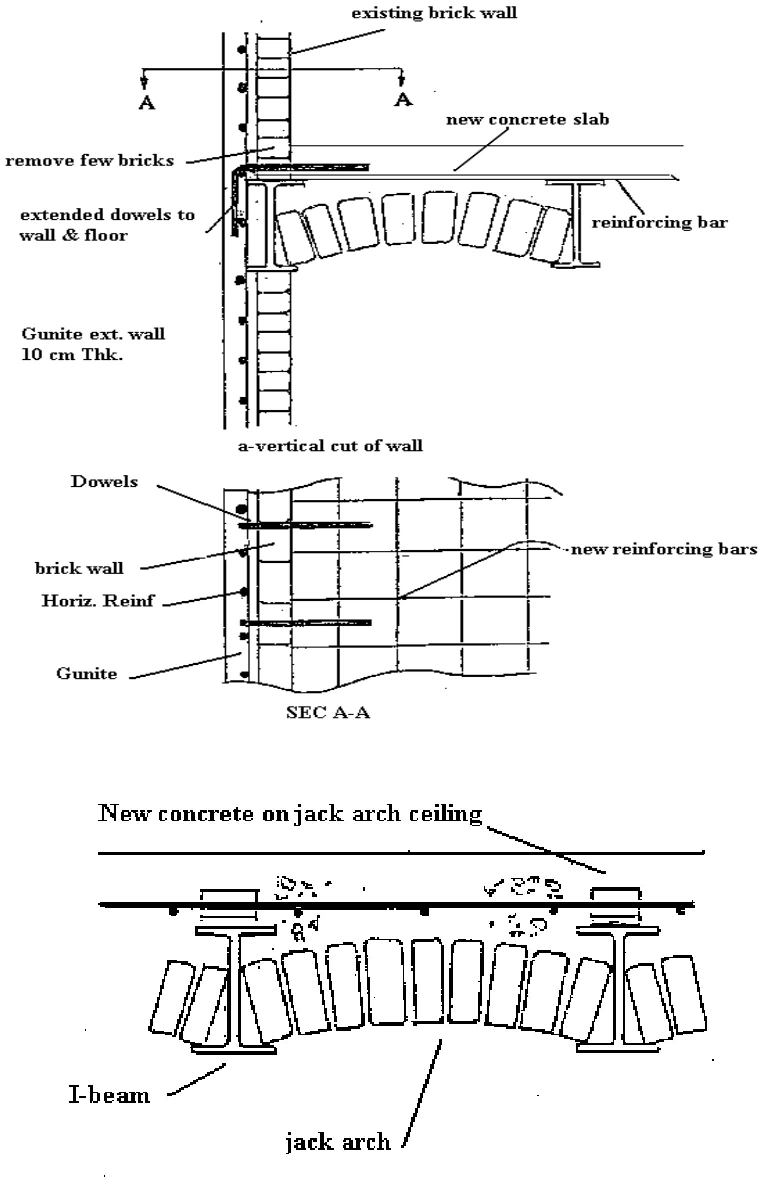


Figure 5- Simple and effective way of strengthening by increasing the existing building's force resistance capacity

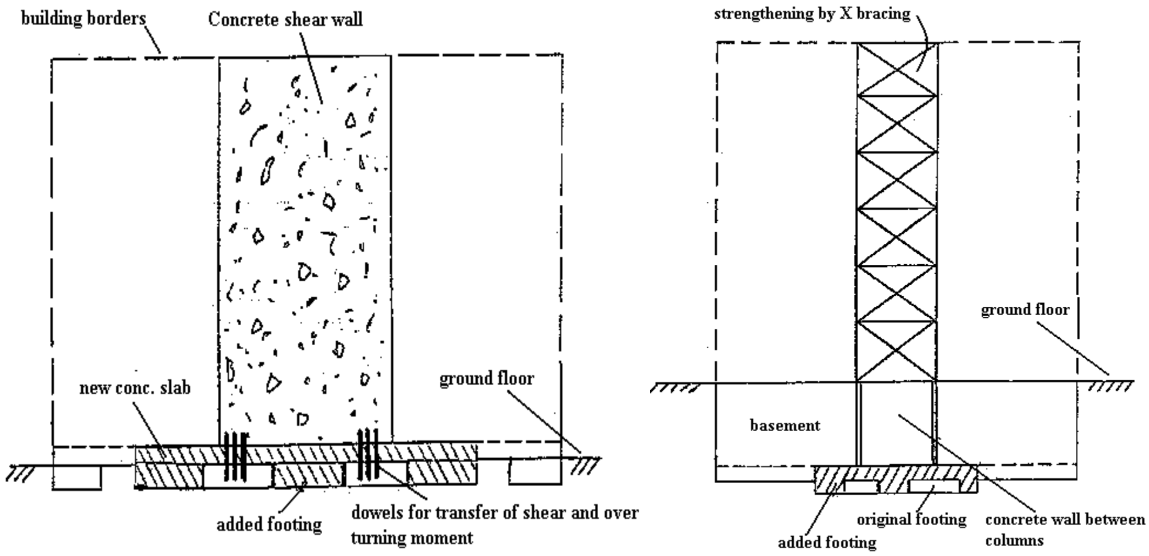


Figure 6- Some simple and effective means of strengthening by increasing the existing building's force resistance capacity

Economical Strengthening of Concrete Structures

If building's function does not allow addition of shear walls, the framing members have to be strengthened. The cost effective solution is using steel jacket around them and filling the internal gap by grout or Epoxy resin (expensive). The cost of this application is around 150-200 USD/m^2 of covered area.

The cost of applying carbon fiber (CF) is approximately 250 USD/m^2. This does not include the cost of debris removal, cleaning, surface preparation prior to CF application. It also does not include the cost of subsequent finish work to bring the structure to liveable state.

The floor RC slab can be strengthened by:

- Adding a new layer of concrete to the existing floor slab. Using concrete glue on the old surface, installing shear keys as anchors to attain the bond between the new and old concrete layers.
- Using carbon fiber on the bottom surface. 250 USD/m^2 for material, plus about 10 USD/m^2 for design and labor or a total of 260 USD/m^2.

Concrete Shear Wall on All Building Types

The unit cost of shotcreting may be obtained based on some basic assumptions and a typical building, assuming an average 4 story building with regular and rectangular plan, as follows:

Assume two shear walls at each of the four corners. Each shear wall is 5m long and 3m high (15m^2) and 20cm thick. The cost of material and labor to construct one such shear wall at each floor is determined by considering the following labor and material costs:

- Material removal	13
- Surface preparation	30
- Drilling holes (at 30cm O.C, 110 holes)	150
- Installing anchors labor and material (L&M)	482
- Installing reinforcing mesh (L&M)	255
- Cost of mesh and Application of shotcreting (L&M)	188
- Touching and smoothing the surface	38
- Debris Removal	13

Total 1,169 USD

Allowing 20% for contractor's profit: 1,169 x 1.2 = 1,403 USD.

Thus the estimated cost of installing a shear wall with, about 20cm thickness and 15 m^2 surface is about 1,403 USD. Thus thee unit cost is roughly 1,403 USD/15 m^2 = 94 USD/m^2. This unit cost may be used to estimate just the construction of shear wall alone. No other side costs associated with the strengthening process was considered.

Steel Shear Walls

Steel shear walls appear to be simpler to install and less time consuming. In this approach a framing with sufficient cross sectional area is installed within a panel surrounded by columns and beams. For RC beams and columns anchor bolts would secure the steel framing. The steel shear wall would be attached to the infill steel framing by bolts or by welding. This method should be less time consuming. Again as before, assuming a shear wall of 5 x 3 x 0.20 m at a floor; its cost estimate would be:

- Material removal	13
- Drilling holes (@ 30cm O.C.)	30
- Installing anchors	482
- Attaching framing 45 kg/m for16m @ 0.75/kg (L&M)	540
- Attaching plate shear wall (L&M) (Assuming Average 1.5 cm plate thickness.@ 5 USD/kg)	930
- Debris removal	13
Total	2,008 USD

Allowing 20% for contractor's profit: 2,008 x 1.2 ≈ 2,410 USD
The unit cost is roughly 2,410/15 m^2 ≈ 161 USD/m^2

Steel Bracing

Similar to masonry building, RC structures are heavy. Also the allowable drift in members is limited; therefore, the required bracing member sizes would be heavier than steel framing. Its cost estimate would be:

- Cleaning the area of jacket (4 joints)	50
- Drilling anchor holes	40
- Installing anchors, typically 4 on each face (It is assumed 32 bolts are used for 4 corners @ 13 USD each to install)	400
- Installing 4 Jackets at the beam-column joints	180
- Material for jacket & injecting grout (4 x 200 kg @ 0.75 USD/kg)	400
- Welding or bolting the bracing	420
Total	1,490 USD

Allowing 20% for contractor's profit: 1,490 x 1.2 =1,788 USD

The unit cost is roughly 1,788 USD/15m^2 = 120 USD/m^2

Strengthening Khorjini Connection

The steel framing with khorjini connections effectively support gravity loads with not so much lateral load resistance, Tahooni [1]. In order to enable khorjini system to resist lateral load, one has to consider the followings:

- Strengthening the foundation
- Strengthening columns
- Strengthening beams

- Strengthening the connections at different levels depending on whether bracing is allowed or not
- Adding a new bracing system

The strengthening will be by simply exposing beam and column members and adding stiffening plates at their connections. The strengthening of column shall extend to the base plate and include the foundation. The cost of strengthening the beam–to-column connection is about 200-250 USD per connection depending on the degree of needed strengthening.

Strengthening By Using Base Isolation System (BIS)

The Base Isolation system should be particularly considered for hospitals, schools, governmental buildings, and recent short to medium rise residential buildings. The reason for this, among others, is its relatively low cost and the minimum disturbance that the implementation of BIS may cause. Implementing Base Isolation System is quite economical comparing to the traditional construction practice. The saving is higher for strengthening existing buildings compared with the construction of new buildings.

Foundation

If space limitation allows, the foundation area may be increased and the new and old parts properly tied. Otherwise one may resort to using piles. A strip of concrete or steel member with rectangular cross section that would support the so-called weak existing foundation may tie the top of piles together. Piles at any diameter would be dug by labors at a cost of 14 USD/m^2 . Reinforced concrete cost is about 50 USD/m^3.

Rule of Thumb for Strengthening Cost Estimate

Another approach for rapid estimating strengthening cost is using the so called rule of thumb in order to check the cost benefit of strengthening as opposed to rebuilding.

Assume a typical 4 story building as a base to estimate the time and cost of a typical strengthening project. The cost of constructing a new building is given below. This cost may be used as a guide to determine the feasibility of retrofitting as opposed to demolishing and rebuilding a new building.

Good quality residential building	175 – 250 USD/m^2
Hospital building (without equipment)	315 – 375 USD/m^2
School buildings	150 – 200 USD/m^2

It is generally accepted that 5% of the above unit costs is related to providing the lateral load resisting system in the structural framing, according to Iranian Standard 2800.

The general consensus among the engineers, with hand on experience, is that the anticipated cost and schedule of strengthening should be given as a range and as a percentage of the cost of constructing a brand new building.

The anticipated cost of typical strengthening is estimated at about <u>20 to 30%</u> (or even higher for old URMs') of the new construction. The lower range of the above estimate applies to low cost residential and also to schools. Most school plans and their construction are almost standard, besides the strengthening of schools can be done mostly at the exterior of the building and during long summer session when they are closed. On the other hand the higher range of strengthening cost is justifiable for hospitals, governmental, hotels, and tall residential buildings, in which the occupancy rate is high. In busy buildings the construction schedule and procedure should be adjusted in such a way as to cause the least disruption of daily activity or business, the extra cost of construction is to be accounted for. For example, the cost of paying overtime, extra pays to night shift workers; noise control, etc. are some of the added costs of strengthening that may be mentioned.

CONCLUSIONS

Several levels of strengthening may be applied to buildings, based on the scenario earthquake developed in each Micro zone, as well as the engineering assessment of the existing buildings. Furthermore, different strengthening method should consider implementation time and their cost effectiveness in comparison with rebuilding them. Using rule of thumb would be a fast approach to estimate the strengthening budget. The subsequent step is to carry out engineering design to arrive at detailed strengthening cost estimate. The simple solutions using locally available material and the experimental results in the literature worldwide may greatly simplify the decision making process on the strengthening methods to be implemented.

In developing countries the quality of construction workmanship is lower than the developed countries, because of using unskilled work force and probably lower quality material. Therefore, applying the concept of increasing lateral force capacity of the building compared to increasing structural ductility capacity appears to be simpler and a more viable solution. Considering lower labor cost with respect to material cost the emphasis should be on offering solutions that use more labor and less material. The dead weight reduction in the first place is a sensible and easy to achieve way of increasing buildings' strength. Finally the strengthening program in developing countries should be a gradual process starting with the simplest solutions; such as securing walls, veneers, parapets, etc to more complicated and expensive ones, in order to enable the authorities to allocate the appropriate budget without imposing a major burden on the nation's expenditure priorities.

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