Structural Performance

discussion of performance issues relative to extreme events

Pakistan Earthquake Reconstruction and Recovery Program

Structural Engineering Considerations

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On October 8, 2005 at 8:50 a.m. local time, a magnitude Mw=7.6 earthquake struck the Himalayan region of northern Pakistan and Kashmir. The earthquake caused widespread death and destruction in the region. The Pakistan government has launched a reconstruction and recovery program through the Earthquake Reconstruction & Rehabilitation Authority (ERRA), who has undertaken the enormous task of reconstruction and rehabilitation in the earthquake affected areas with the aim to "Build Back Better" in terms of physical infrastructure, size and scope of activities and quality of services to the people. This reconstruction program is funded by multiple private and public donor organizations, including a number of international donors. One such program which aims to build and strengthen goodwill between the Pakistani and American peoples is funded by the United States Agency for International Development (USAID). Camp Dresser McKee (CDM) is delivering the Pakistan Earthquake Reconstruction and Recovery Program (PERRP) to reconstruct schools and health facilities. The program is part of the $1.5 billion in aid that the U.S. government is providing to Pakistan over five years to improve economic growth, education, health and governance to assist with earthquake reconstruction. Coffman Engineers Inc., Los Angeles office (CEILA) was selected as a specialized structural engineering consultant to focus on earthquake resistant design and construction for the buildings that are proposed to be built under the program. PERRP is a very interesting and challenging project from a structural engineering perspective. This project started with a plan of construction for over 200 earthquake resistant public buildings, which included small clinics, primary schools, high schools and some relatively larger healthcare facilities. During the first year (Oct 2006 – Oct 2007), CDM developed a schedule to complete the design of 40 such buildings and to start the construction as soon as bids were awarded. The consultant team began this project with the assumption that all design work would be performed by local A/E firms. Due to various factors, including very high workload for local design firms resulting from an extremely busy post-earthquake construction market, limited number of properly qualified personnel and an inconsistent level of knowledge and proficiency in earthquake resistant design, it soon became clear that a small design office staffed by American design professionals located in CDM's Islamabad office was needed in order to oversee the work of local A/E firms. As a result, CDM set up such an office led by an American architect and a Structural Engineer (Ahsan Sheikh, P.E., S.E.) from CEILA along with some local engineering/CAD assistants. This group's primary objective was to oversee and manage the design, the production of construction drawings and QA/QC during construction, in conjunction with other groups and project managers/engineer who were part of CDM's Islamabad staff. Prior to the setting up of this local group, CEILA's structural engineers (led by Saif Hussain, P.E., S.E.) had formulated seismic design criteria and a design approach appropriate for this project, keeping in mind acceptable international design standards as well as local applicability and capabilities.

Figure 1: Poor Structural Performance of MICF Buildings During Earthquake. Courtesy of A. Nisar (MMI Engineering EERI).

Deficient Structural System

The design oversight office based in Islamabad started work around May, 2007. At that time, the local A/E firm was attempting to finish their design on two high school buildings. The structural system proposed by the local firms for these two buildings was the same system typically used in building construction in Pakistan, i.e. masonry infilled concrete frames (MICF). A number of the common deficiencies found in such typical systems were evident in early versions of the structural drawings for these projects, such as frame members not properly detailed for ductile behavior, masonry infill walls not reinforced for out-of-plane loading, infill walls not isolated from the adjoining concrete frames, roof/floor diaphragms not properly connected to the lateral system, inadequate layout of footings etc. Furthermore, the design was based on inappropriate seismic design criteria. The design oversight office called for a comprehensive structural redesign of these projects based on a proper and rational structural design approach as outlined below, in accordance with the CEILA formulated basic seismic design criteria and approach mentioned above.

Figure 2: Girls High School, Chowki, located in AJK Pakistan.

It is important to note that this type of flawed structural system (MICF) is quite common, not just in this part of the world but also in quite a few other countries around the globe (*Figure 1*). The performance of MICF buildings has been extensively studied by engineers and researchers all over the world. One such group of leading earthquake design experts, supported by the Earthquake Engineering Research Institute (EERI, Oakland, CA) is World Housing Encyclopedia (WHE).

According to WHE (**www.world-housing.net**), there are more than 37 countries containing high seismic regions across the globe, where reinforced concrete along with masonry is the material of choice for housing and other building construction. Reinforced concrete frames with infill masonry are extensively used for construction in many regions of high seismic risk, such as Latin America, southern Europe, North Africa, the Middle East and south-east Asia. Recent earthquakes across the world, including the 1999 earthquake in Turkey, 2001 earth-quakes in India and Taiwan, 2003 earth-quake in Algeria and more recently the 2005 earthquake in Pakistan, have revealed major deficiencies in these buildings, some of which led to catastrophic collapses causing death tolls measured in the tens of thousands. Early information coming out from the Sichuan province in China, which suffered the M=7.9 earthquake in May of 2008, appears to also corroborate this point.

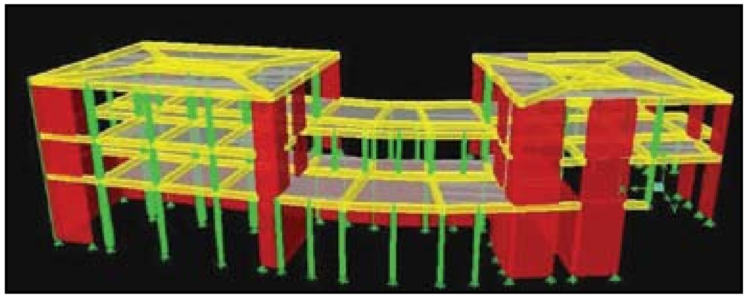

Figure 3: 3-D ETABS Structural Model Of Chowki High School.

Adequate Structural Design

As mentioned above, following consultation between CEILA, CDM and USAID it was decided that the prudent approach for the PERRP project would be to utilize code conforming structural systems properly designed and detailed for a satisfactory level of earthquake resistance, aimed at a "Life-Safety" performance objective in a major earthquake of the type experienced in Kashmir in October 2005. The *Uniform Building Code* (1997 UBC) was selected as the base documentfor the project. The UBC is very well known across the world, including in Pakistan where many provisions of this code are routinely albeit sometimes inappropriately, used by local engineers to design buildings. The concrete design provisions of the UBC, which are essentially the same as the ACI code, are the most commonly used concrete structural design provisions in Pakistan. Given the numerous problems with typical MICF construction in Pakistan, and after a study of various alternatives, it was decided that reinforced concrete shear walls would be used as the primary lateral-force-resisting system for the PERRP buildings. This made eminent sense since, these buildings already had numerous partition or exterior walls called for in the architectural design. A few of these walls could easily be used as shear walls, and other nonstructural walls would be properly designed and detailed to perform satisfactorily in large earthquakes. Reinforced concrete slab-beam-column construction was used to resist gravity loading and reinforced masonry block walls were used as nonstructural partitions. The decision to use reinforced concrete and masonry blocks for wall construction is based on a number of parameters, like abundance of ingredient materials in the region, low cost of construction, easy availability of trained workforce, low maintenance costs and the inherent durability of concrete.

Like most building projects in high seismic areas of the United States, structural engineers sometimes face challenges as they work with architects to ensure adequate lengths of shear walls along the perimeter/exterior of the building. Openings for windows, doors, breezeways etc. have to be contended with to obtain contiguous shear walls piers that run from roof to foundation. The demand for large windows is greater in this region of the world, because classrooms rely primarily on daylight for adequate visibility. The design group, working closely with the local architectural consultants, has managed to obtain adequate lengths of walls along the perimeter of the PERRP buildings. One such example of shear wall layout is shown in *Figure 2*. This is a 17,000 square foot Girl's high school building located in a small town named CHOWKI in the BAGH district of AZAD JAMMU KASHMIR (AJK), the Pakistani controlled region of Kashmir. This building uses the appropriate Importance Factor as per UBC-97 Table 16-K. The site is located close to an active earthquake

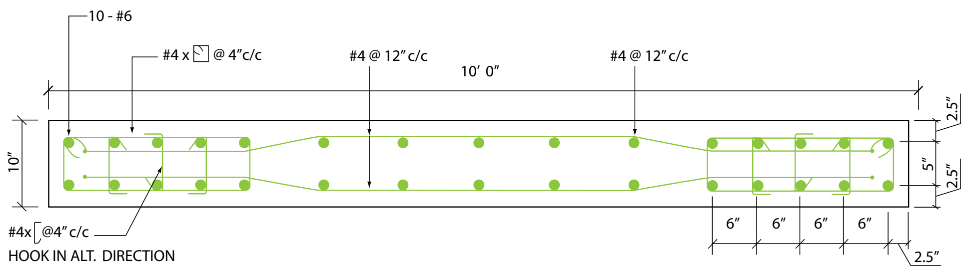

Figure 4a: Plan View of Shear Wall Rebar Layout.

Figure 4b: Construction Photo of a Shearwall Rebar Cage.

fault, Type A, which is in an area classified as seismic zone 4, therefore near source factors Na=1.5 and Nv=2.0 have been used. An R value of 4.5 as per table 16-N, Sd type soil profile with seismic coefficients Cv=0.64Nv and Ca=0.44Na, are used as seismic design parameters. A three dimensional computer model of the building was generated and analyzed on the ETABS computer program. (*Figure 3, page 29*) The shear wall web and boundaries are properly reinforced for ductility (per UBC-97 Section 1921.5.2) as shown in *Figure 4a* and *4b*. Billet steel A615 reinforcement (per Section 1921.2.5.2) is specified in the boundary zones, which is locally manufactured and easily available in the market.

Concrete beam-column members are used to support the concrete floor and roof slabs for tributary gravity loading only. These "frames" are not part of the lateral-force-resisting system. The columns are detailed as shown in *Figure 5* (per UBC-97 Section 1921.7) to maintain support of gravity loading when subjected to the expected inelastic deformation caused by the earthquake forces. When the building frame is subjected to inelastic level deformation, a hinge is typically formed at the top of the column. Providing extra ties in the column (per Section 1921.4.4) keeps the column intact and prevents total or partial building collapse which is the minimum life-safety and serviceability requirement of the building code. The Code requirements for column rebar confinement result in a fairly large number of ties in the columns. The construction contractor's sarcastic comments related to the quantity of rebar specified resemble what engineers often hear from American contractors on concrete construction jobsites in high seismic areas.

A common joke implies that the structural engineer probably has investments in rebar producing companies.

Concrete floor and roof slabs and beams are designed for tributary dead and live loading, which is a fairly routine design procedure for local consultants. In fact, their design of these components for gravity loading is quite efficient and cost effective. Material use is minimized through design optimization. However, diaphragm action and the need for proper diaphragm design of these elements is commonly not well understood by the local consultants. The concept of story shear, drag, collector and chord forces in the diaphragms had to be explained and illustrated. This eventually led to the proper design of these seismic force resisting elements, and to their inclusion in the design drawings.

Concrete Masonry Unit (CMU) block walls have been used for partitions and exterior walls for these projects. These blocks are locally manufactured (per ASTM C90) and are readily available in the market. The block walls are isolated at the top to allow for the in-plane movement of the diaphragm, but anchored and properly reinforced for out-of-plane loading (per Section 1633.2.8) as shown in *Figure 6*, so the walls do not collapse and injure or kill occupants or pedestrians during an earthquake.

Construction Considerations

The structural performance of buildings in large earthquakes, where ductility is of greater importance than simply the elastic strength and stiffness of structures, depends heavily not only on proper structural design and detailing but, perhaps more importantly, on proper quality control during construction. This aspect of delivering earthquake-resistant building structures for this project was particularly emphasized by the CDM/CEILA team. A concerted effort was made to develop proper observation and inspection requirements duly noted in the specifications, training the inspectors and keeping close tabs on the construction of seismic system

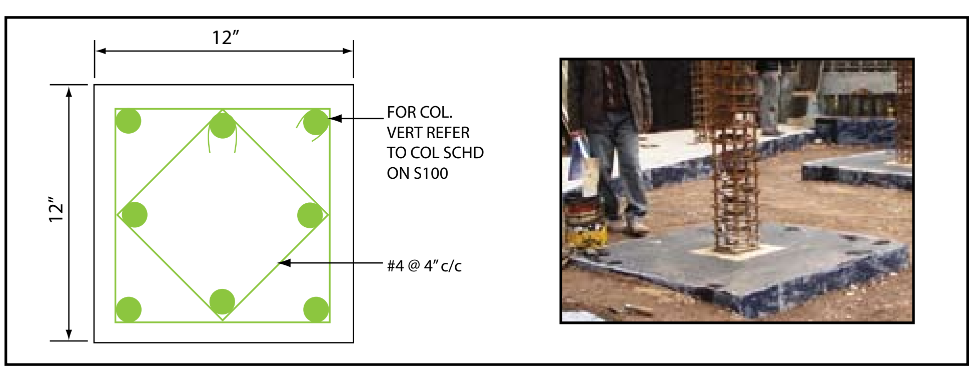

Figure 5: Column Rebar Layout Detail and Column Rebar Cage Construction.

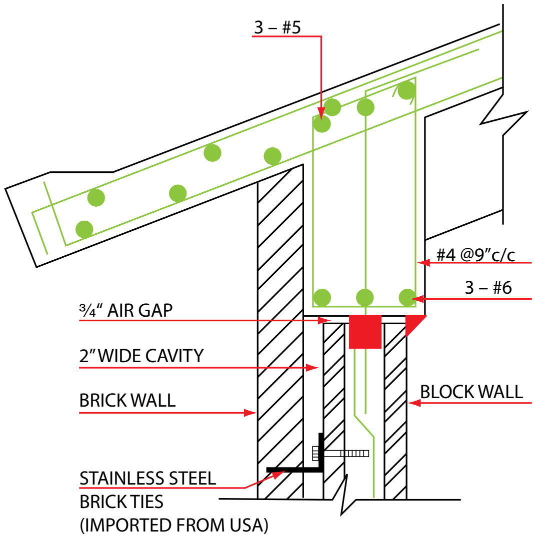

Figure 6: CMU/Brick Veneer Connection Detail.

elements on-site. As part of this process, regional inspection offices in the vicinity of actual construction sites were set up. These inspection offices are staffed with experienced inspectors and resident engineers who are further trained on the UBC-97 Chapter 17 inspection program. A detailed construction inspection program which outlines the various types of inspections, different stages for these inspections and inspection frequency has been developed (*Figure 7*).

Summary and Conclusions

The PERRP Program, funded by USAID, aims to build hundreds of adequately earthquake-resistant schools and healthcare facilities in northern Pakistan following the devastating earthquake of October 2005. Though there are a number of well educated and knowledgeable structural engineers practicing in Pakistan, CDM/CEILA's experience has shown that the overall practice of earthquake resistant structural design and construction often does not meet the standards that one might expect in high seismic regions. It is also often mistakenly assumed that systematic, well planned and effectively implemented improvements in design will end up substantially increasing the cost of building construction in these regions. The PERRP experience has shown that this is not quite the case. With very modest increases in total construction costs resulting from the adoption of the measures explained above, a significant enhancement can be obtained in the expected seismic performance of newly built structures, thus saving lives and reducing damage in sure-to-come future temblors.▪

Types of Work	Continuous	Periodic	Comments
Soils			
Footing's Base Soil			Geotech Engineer Inspection & Approval Required
Grading, Excavation & Fill			Ref. Project Specification
Concrete			
Placement of Reinforcing Steel			
Welding of A706 Reinforcing Steel for Embeds Larger Than #5			
-#5 and Smaller			
Bolts Cast in Concrete			
Placing of Reinforced Concrete			
Taking Off Test Specimens			
Structural Welding			
Single Pass Fillet Welds Not Exceeding 5/16"			
Fillet Welds Exceeding 5/16"			
Groove Welds (Full or Partial Pen)			
Welded Studs			
Structural Masonry			
Prism Preparation / Test Specimens			
Unit Placement			
Placement of Reinforcing Steel			
Grout Space			
Grout Placement			
Other			
Reinforcing Steel Mechanical Splices			Per ICC/ICBO Evaluation Report
Adhesive Anchor Installation			Per ICC/ICBO Evaluation Report
Expansion Bolt Installation			Per ICC/ICBO Evaluation Report
Masonry Veneer Anchors			

Figure 7: Construction Inspection Program.

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