SEISMIC REHABILITATION OF BUILDINGS-RESEARCH ACCOMPLISHMENTS/RESEARCH NEEDS

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SUMMARY

In 1980, there was virtually no research reported in the literature regarding seismic repair and strengthening of buildings. There were a few papers by engineers describing the repair or strengthening of a particular building—generally one that had been damaged in an earthquake. But there were no meaningful studies to guide engineers for repair and strengthening of buildings that were damaged by an earthquake or that were expected to perform inadequately in an earthquake prone region.

About that time, a unique collaborative effort to address these needs began. The research effort involved a university faculty that had a large structural engineering graduate program and ongoing experimental structural research activities. The collaboration was with a consulting structural engineering firm, located in an area of high seismic exposure. The firm was actively involved in evaluating existing buildings for seismic performance and recommending strengthening for improved seismic response. It had an established record of work in this field over a long period. The engineering firm proposed the needs, designed proto-type buildings and potential strengthening solutions. The University responded with a series of laboratory experiments to determine how various materials could be combined for improved seismic performance. Both teams joined in the interpretation of data and development of recommendations for designers to use on rehabilitation projects.

The purpose of this paper is to focus on the collaborative process, why it worked so well, some of its accomplishments, what the process fostered, and what is still needed from the research community.

THE COLLABORATIVE PROCESS

At a workshop on Earthquake-Resistant Reinforced Concrete Building Construction in Berkeley, California in 1977, organised by Prof. V. V. Bertero, the primary author presented a paper on the applicability of earthquake research from the user's viewpoint. The paper recommended that research projects be conceived to produce results transferable to practice and encouraged researchers to obtain some practical design experience. The paper strongly encouraged research projects to incorporate advisory committees of practising engineers or a stronger role with practising engineers serving as consultants to research projects to steer the research towards the needs of the users.

Subsequent to the Berkeley Workshop, the collaborative process between The University of Texas at Austin (UTA), and Degenkolb Engineers (DE) in San Francisco was initiated and is described in this paper. It began in the spring of 1980, when Prof. Jirsa spent part of a semester sabbatical leave and a summer in the office of Degenkolb Engineers. During that stay he became familiar with the extensive number of existing buildings that were being evaluated by Degenkolb Engineers, with the prediction of their potential seismic performance, and with the concepts of seismic strengthening. At that time, most of these evaluations did not progress beyond the report stage, but the few projects that did proceed through construction documents reflected the extensive engineering judgement that was required and the lack of research results to sharpen that judgement.

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That experience led to the development of a collaborative research proposal on methods to strengthen nonductile reinforced concrete moment frames for improved seismic performance. UTA and DE obtained separate grants from the National Science Foundation that were based on identical technical proposals. DE was responsible for developing prototype buildings that required strengthen and developing solutions for modifying their response. UTA was responsible for adapting those solutions to large size (3/4 scale) components and sub-assemblies that could be tested using the facilities at UTA (Ferguson Structural Engineering Laboratory). UTA graduate students performed final design studies, specimen fabrication, and testing. Engineers from DE were present for many of the tests and participated in the evaluation of the test results and conclusions. Both teams published papers describing the results, with UTA focusing more on complete documentation of the results and DE focusing more on design guidelines and recommendations for practising engineers.

The initial grants began in 1982 and continued into the mid 1980s. A second pair of grants in the late 1980s focused on infilling concrete frames including infills with windows. Subsequent grants in the 1990s allowed further collaboration on steel jacketing of concrete columns and an innovative infill procedure with small precast concrete elements.

RESEARCH RESULTS

Frame Modification

The initial grants focused on non-ductile concrete frame strengthening. A three-story, two-column sub-assembly of a strong beam-weak column frame was the basic specimen extracted from the prototype building. The prototype non-ductile frame was typical of a particularly vulnerable structural system in earthquake zones. Before building the large test frame, much had to be learned regarding the attachment of new concrete to existing concrete for shear and tension. At that time only limited test information from epoxy manufacturers was available for epoxy-grouted dowels or bolts in concrete. Tests of epoxy-grouted dowels in tension and epoxy-grouted bolts and dowels in shear provided a basis for design guidelines. Information on the depth of dowel installation, the importance of clean holes (removing the drilling dust so the epoxy can bond well with the concrete hole surface), and the need for quality control of dowels installed in the field through inspection and proof loading was obtained. The three-story frame was constructed and strengthened with wing walls using the data from the dowel tests to develop a shear wall-frame structural structure (or shear wall with regular pierced windows).

The strong beam-weak column prototype was typical of at least six similar buildings DE had evaluated. The buildings were typical of 1950s construction with exterior spandral beams 7 to 9 feet (2.3 to 3 m) deep and 8 inches (200 mm) thick with short columns with clear heights of only 4 to 5 feet (1.3 to 1.7 m) long. Such short columns are likely to fail in shear under lateral ground motions. At the time these buildings were designed they were considered to be a very efficient structural system, albeit of non-ductile concrete. The frame was very stiff and architects liked the nearly continuous windows. The research team felt this system represented the most difficult non-ductile concrete frame to strengthen. The same research results would be equally applicable to other less difficult frames.

After the wing wall test was successfully concluded, the wing walls were removed by selective saw cutting and a steel diagonal bracing scheme was added to the test specimen. In the original proposal, it was anticipated that several large subassemblies would be build but construction costs exceeded estimates and the frame was "recycled." The design of the bracing solution built on previous work in Japan. A similar strengthening scheme had been executed in Sendai following the Tokachi-oki earthquake. Reports from that project provided valuable information for the design of the braces. The steel diagonally braced concrete frame performed very well and was loaded to limiting stroke of the hydraulic jacks. Large cracks formed in the concrete, but the braced structure remained stable. One major problem with the construction was difficulty in developing the capacity and ductility of the braces through field welding of the connections. The steel elements were rather small and the lack of clearance and space made it hard to conduct and inspect the welds. DE engineers utilised this experience to improve the designs of welded connections in future projects.

Inspired by the Mexican earthquake of 1985, the permanently deformed concrete frame went through one additional experiment. The steel bracing was removed and all loose concrete was removed from the permanently distorted frame. The columns were jacketed with new concrete with ductile confinement and just enough strength to achieve a capacity 20% in excess of the deep beams as required by U.S. design codes. The use of encasement to recover column strength and stiffness provided a demonstration of the viability of this strengthening solution for severely damaged column elements.

Infills During the second grant period, the focus was on concrete frames strengthened using infills and methods to improve the tension capacity of lap splices in columns designed for compression only. Such laps are subjected to high tensile forces when the frame with the added infill is loaded laterally. Infills were cast in place eccentrically with the frame and shotcreted as a solid infill concentric with the frame. Some of the infills contained a door and others had a sizeable window. The laboratory-installed shotcrete was not unlike field placed shotcrete with some critical voids at the back form under the beam soffit which created their own research project on repair techniques. An epoxy repair was utilised to keep the research focus on the frame/infill interaction without being limited by a new weak link (voids at the infill/beam interface) in the system. The data was used in establishing guidelines for infilling concrete frames with new concrete walls. Under subsequent grants, an innovative infill scheme was developed using small precast concrete segments with keyed edges designed so they could be moved across normal floors on a light weight forklift and erected as an infill with narrow grouted or cast-in-place joints. Shear lugs to columns were added for better shear transfer along the infill/frame boundaries. Holes were cored through beams for continuous vertical infill reinforcement. The scheme proved extremely successful in the experiment and offers what appears to be an economical procedure for strengthening low rise frame structures.

Steel Jacketing

Another major phase of the collaborative project involved steel jacketing of nonductile columns. Extensive experiments on square and rectangular concrete sections that were either shear or flexure critical with short lap splices typical of normal frame columns were extremely illuminating. The experiments verified that steel jackets alone do not confine for ductile performance, and just as large concrete columns need crossties or interior ties, steel jackets need intermediate bolts into the concrete core to be successful. Vendors of carbon-fibre wraps who are currently marketing their proprietary projects very aggressively need to benchmark their products against the results involving steel jackets.

RESEARCH BY OTHER TEAMS

In the early 1990s, the National Science Foundation sponsored an initiative on seismic repair and strengthening and a series of projects were executed in various laboratories throughout the United States. With strong encouragement from NSF for research/design collaboration, many of these projects were collaborative with design engineers providing guidance to the University research teams. These projects focused on strengthening various types of seismically deficient structures and several projects dealt with new materials and their applications to seismic repair and strengthening. NSF provided a means for all involved on these projects to meet several times and exchange results and ideas. Such interaction was critical to the timely implementation of results and for maximising the acquisition of meaningful data.

Finally, there has been a great deal of useful research in recent years applicable to repair and strengthening of structures for improved seismic performance. Extensive tests on expansion anchors and epoxy anchors in the United States and Europe have provided insight into attachments to existing concrete and the effects of cracks on their performance. The manufacturers and advocates for seismic isolation devices and dampers have performed extensive research giving designers further information for the application of these various devices. The impact of the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake prompted many other studies and case histories of repairing and strengthening damaged buildings. Furthermore, these earthquakes have awakened many building owners and corporations to the need to evaluate the seismic vulnerability of their building inventory and to strengthen many undamaged, but inadequate, buildings. The many buildings strengthened recently in California will provide a research bonanza following the next large damaging earthquake.

Implementation

The culmination of much of this research has been the recent development of guidelines sponsored by the Federal Emergency Management Agency (FEMA) of the U.S. government. A series of guidelines to evaluate the potential seismic performance of existing buildings has progressed from ATC-14 to FEMA 178 to FEMA 310. A new guideline for strengthening existing buildings known as FEMA 273 was recently developed and that document is currently undergoing further refinement and testing with trial designs. Many engineers are using these documents, but for certain types of structures and some unusual buildings they can produce illogical results so continued refinement will be needed.

RESEARCH NEEDS

No paper discussing research results and the success of research would be complete without a discussion of research needs. Everyone naturally wants to market for their next project and the research community is not unique in that respect.

A considerable knowledge base has been developed in the past 20 years and engineers can now approach a seismic rehabilitation project with some confidence that their design will perform reasonably well. More research is clearly needed on the new products becoming available to assist in seismic rehabilitation projects. Most of these products are proprietary and their research has been conducted by in-house or potentially biased researchers looking for favourable results. These products need independent testing by impartial researchers so their performance can be understood without reservation or question.

There are certain structural systems where analytical and experimental performance is not well correlated. One example is the FEMA 273 inelastic push-over analysis with respect to substantial shear wall systems. The analysis seems to consistently indicate lack of capacity and a need for strengthening whereas judgement and experience observing actual earthquake performance would suggest that these systems are adequate or require only minor strengthening. Empirical design procedures for shear in concrete seem to result in conservative results for such shear walls. Another major problem is with buildings that have mediocre seismic detailing (neither clearly deficient nor clearly meeting current requirements) and thus having an uncertain potential seismic performance. Determining how extensively to strengthen these structures requires research that relates to the uncertainty of the severity of expected earthquakes over the lifetime of the structure.

While much of the research on new materials can be carried our with relatively small scale tests and with analytical studies that usually are helpful, there is a need for experiments at large or full scale to verify systems and design approaches. A large magnitude earthquake in California, where many recently strengthened buildings are located, would expand our knowledge base and confidence considerably. However, that can be an expensive and uncertain means of conducting research. Clearly some large system tests are needed to pull together much that we have learned in recent years in small scale testing.

Finally, the issue of performance based design is gaining momentum and is being requested by numerous building owners. Hospitals and many critical manufacturing and business centres need to remain operational during and immediately after an earthquake or to be back in operation in a few days. Owners are considering such upgrades due to the cost of relocating support facilities and infrastructure. Research is needed to clarify how extensive these upgrades must be to accomplish high-level performance objectives. A well-conceived system for which the response of the system vis-à-vis the earthquake motions is considered is likely to be preferable over a system relying only on brute lateral strength. Clearly, the whole issue of performance based design and the realisation of higher states of performance, both for new structures as well as strengthened existing buildings, presents a significant research agenda needing careful planning and thoughtful consideration. The collaborative process will certainly be beneficial in this task.

VALUE OF COLLABORATION

Our collaborative projects have clearly shown the advantages of research universities and faculty working closely with practising design engineers. The design engineers can focus the research to the needs of the profession so the results can be used readily by practitioners and do not become dusty tomes on a shelf.

Design engineers participating in such research projects have to recognise that research, or the design of research experiments, is different from actual building design. In normal building design, it is easy to add a few extra inches of concrete or reinforcing bars to be sure a member is strong enough, stiff enough, or ductile enough. Design engineers gain some comfort and the ability to sleep at night from such decisions. But in experimental research, the experiment must be designed without such margins, or comfort level, so the actual strength or response can be determined to form the basis of guidelines or codes for minimum acceptable performance. The difference in design objectives creates a different way of thinking, which must be followed if we, as an engineering community, are to use the research results properly and provide economical designs for the building owners. Design engineers spending a few days in the laboratory also significantly increase their understanding of structural performance at extreme deformations. It may be the only time most designers will have an opportunity to "see" their designs perform under severe loads and deformations. Such knowledge will enable them to better understand the relationships between damage levels and deformations and to appreciate the differences between various failure modes.

CONCLUSIONS

Research accomplishments and research needs in the general areas of seismic repair and strengthening of reinforced concrete buildings have been the focus of this discussion. Specifically, the emphasis has been on a collaborative process where university researchers work closely with practising design engineers who specialise in repairing and strengthening seismically deficient structures.

The collaborative process has been demonstrated to benefit the conduct of research and to improve implementation of findings. As a result, experiments are focused on the needs of practising engineers trying to improve life safety in seismic regions. The results of collaborative research tend to be presented in forms that can be readily used by practitioners in their projects. The success of this process should encourage others to develop projects conducted in this manner.

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