Paper No. 2099. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC REHABILITATION - APPLICATIONS, RESEARCH AND CURRENT NEEDS

UGUR ERSOY

Department of Civil Engineering, Middle East Technical University
Ankara, Turkey

ABSTRACT

Seismic assessment and rehabilitation of engineering structures are briefly discussed. Research needs in these areas are highlighted. A simple method for assessment is given as an example. Experimental research at the Middle East Technical University on jacketed columns and infilled frames are summarized. Practical applications of test results are discussed.

KEYWORDS

Seismic rehabilitation; repair; strengthening; assessment; jacketed columns; infilled frames.

INTRODUCTION

Seismic rehabilitation is the operation to bring up the structural system or some structural members to a specified seismic performance level. Seismic repair is the rehabilitation of a damaged structure to ensure satisfactory performance under a prespecified seismic action. Seismic strengthening is the rehabilitation of an undamaged existing structure to upgrade its seismic performance to a specified level (Ersoy, 1992).

In the past ten years major earthquakes have caused considerable damage to buildings and bridges in various parts of the world. After such earthquakes comprehensive rehabilitation programs had to be carried out to bring the damaged and undamaged structures to an acceptable level of structural safety.

Recent earthquakes also exposed the vulnerability of many buildings and bridges, in particular those which were designed and constructed prior to the development of modern seismic codes. Preliminary studies carried out on existing structures built in seismic regions revealed that very extensive rehabilitation work is required to upgrade these structures so that their risk for damage in probable future earthquakes is reduced.

Implementation of such programs focused the attention of engineers on seismic rehabilitation and initiated extensive research on the behavior of rehabilitated structures and structural members.

Before intervention (repair or strengthening) a detailed investigation should be conducted to determine the structural characteristics of the structure. This operation is called assessment.

ASSESSMENT

Data collected at the assessment stage are used for evaluations to be made related to the seismic performance of the structure. As a result of this evaluation, the structural engineer decides whether repair or strengthening is needed.

The data to be collected surely should include floor plans, sizes of structural members, locations, and types of infill walls and observed damages (cracking, crushing, buckling of bars etc.). Depending on the method to be used for evaluation, strength of concrete and reinforcing steel, reinforcement in structural members and soil data are also needed. If the structure is damaged, a sound diagnosis should be made to identify the cause or causes of observed damage.

Seismic evaluation of an existing structure is a very difficult task. It involves numerous uncertainties such as the strength of materials and stiffness of members which have imperfections and weaknesses. The stiffness is reduced due to time effect and micro or macro cracking. In seismic evaluation, the effect of nonstructural elements such as infill walls should also be taken into consideration. The engineer should try to estimate the structural characteristics as accurately as possible using the data available. However, be should realize that no matter how detailed the collected data are, structural characteristics estimated are by no means exact values!

In the analyses made to evaluate the seismic performance of an existing structure, the engineer should take into account the possible variations in the structural characteristics estimated. Therefore upper and lower bound analyses leading to envelope solutions are recommended for decision making.

It should be pointed out that the present methods for evaluating the structural characteristics are quite primitive and time consuming. Research leading to more accurate and faster evaluation methods and development of instrumentation for this purpose should be encouraged.

When the building lot to be evaluated is very large, then the classical comprehensive evaluation methods become unfeasible. Also, a large building lot to be rehabilitated may require investments beyond the budget allocations. In such cases the feasible solution will be to make a priority list by selecting buildings with high vulnerability.

Detailed data needed for a comprehensive evaluation and analysis required is also very time consuming and expensive. Also the decision delated to vulnerability can only be made by the judgement of experienced engineers. Therefore we need to develop some simple methods and criteria for initial filtering of the building inventory. Such methods and criteria should not be time consuming and should not require expert opinion.

Istanbul can be taken as an example. The city has a population over ten million and a large portion of the building lot do not comply with the requirements of the Turkish Seismic Code. The governmental buildings in Istanbul alone exceed three million square meters. A detailed and sophisticated evaluation would take years.

The need for simple criteria to select buildings with high vulnerability and assign priorities to such buildings for rehabilitation is obvious. Since the construction type and quality are not same in different countries, such criteria should be calibrated using the data obtained for that country.

The work of Hassan and Sozen can be given as an example for such a simple approach (Hassan et al., 1996). They have calibrated their technique using the data obtained from the 1992 Erzincan (Turkey) earthquake. The criterion considers two indexes, column index and wall index. Column index is obtained by dividing 50% of total column area at the base by the total floor area (summation of floor areas at all levels) of the building. Wall index is obtained by dividing the total area of walls (strong direction) by the total floor area.

Wall area includes unreinforced masonry infills. Infills are added to structural walls by dividing the area by ten.

In Figure 1 the values of the wall index has been plotted against the column index. The data identified as, moderate, light and none refer to 46 government buildings inspected after the 1992 Erzincan earthquake. As can be seen from the figure this method provides a useful tool for ranking the buildings with respect to their seismic vulnerability.

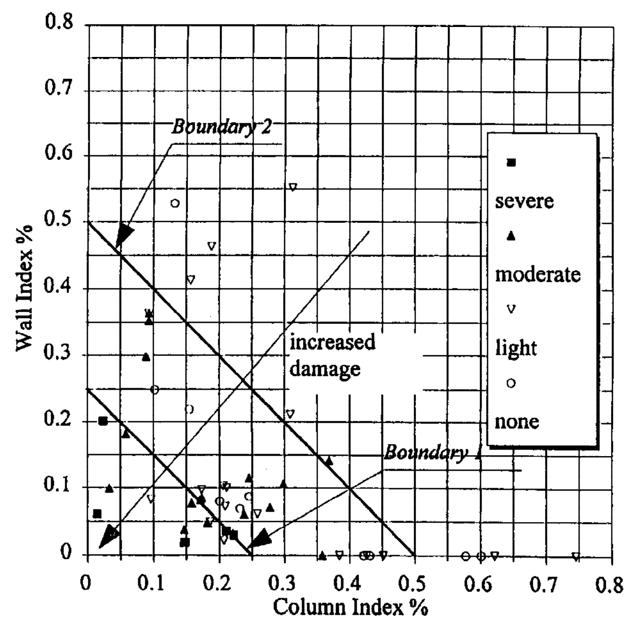


Fig. 1 Ranking of buildings in Erzincan (Hassan and Sozen)

Based on Figure 1 one can rank existing buildings. If the wall and column indices define a point within the triangle marked as "Boundary-1", that particular building should be given priority for rehabilitation as compared to buildings which fall outside of this boundary.

SEISMIC REHABILITATION METHODS

Seismic rehabilitation of structures can be classified into two groups; (a) member rehabilitation and (b) system rehabilitation or system improvement (Ersoy, 1992).

Member Rehabilitation

Members without adequate strength and/or ductility can be rehabilitated using various techniques. The most commonly used technique to improve the performance of columns and beams is jacketing. Jacketing can be made either using steel structural shapes or by enlarging the cross-section of the existing member with a new reinforced concrete shell.

Rehabilitation can also be carried out by bonding steel strips to the members. However the application of this technique is very limited. It should be pointed out that one of the weakness of this method is its fire resistance.

The basic concept of the most commonly used technique of jacketing is simple, but the actual behavior involves many uncertainties such as,

* How is load shared between the existing member and the jacket?
* How much continuity is provided by the jacket?
* Does jacketing also improve the joint behavior?
* If the jacketing has to be made without unloading, will it still be effective?
* Can the jacketing techniques developed in laboratories be applied conveniently in real buildings?

Experimental research done in the past ten years has improved our knowledge on the behavior of jacketed members. Most of the questions related to jacketed beams have been answered by the research work. However such a statement can not be made for columns. Further research is needed to clarify the behavior of jacketed columns (Ersoy, 1992).

System Improvement

In recent earthquakes it has been realized that inadequate lateral stiffness is the major cause of damage in buildings. Undesirable seismic behavior due to well known weaknesses of the structural system, such as strong beam-weak column, soft story, short column etc. has also led to considerable damage.

The most effective way of improving the behavior of such buildings, where unsatisfactory seismic behavior is inherent in the system, is to provide adequate number of structural walls. Such walls not only increase the lateral stiffness significantly, but also relieve the existing frames from the lateral loads. If the walls have adequate stiffness and strength to take the total lateral load, then the weaknesses in frames such as soft story, short column etc. can not lead to undesirable behavior.

Structural walls can be introduced in existing framed buildings by infilling some of its frames. To ensure wall behavior, the infill should be connected to the frame. Such members formed by infilling the existing frames are called infilled frames. The behavior of infilled frames are almost the same as the structural walls if the infill is properly connected to the frame.

The writer has used infilled frames extensively in seismic strengthening of existing framed buildings. This technique becomes very feasible when; (a) framed structure does not have adequate lateral stiffness, (b) structural system suffers weaknesses, such as soft story, short column etc., and (c) the number of frame members to be rehabilitated is beyond feasible limits.

The behavior of infilled frames have been investigated experimentally by various researchers. However there are still many questions to be answered, such as, if the frame columns on each side of the infill do not have adequate stiffness and/or ductility, should they be strengthened also? In many applications columns are found to have inadequate confinement and the lap splices of the longitudinal bars do not meet the seismic code requirements (Valluvan et al. 1993).

In rehabilitating existing nonductile framed structures, the writer has used cast in place reinforced concrete infills. Sometimes use of precast panels as infills becomes very convenient, provided that adequate connection is made between the precast panels and the frame members.

System improvement can also be done by placing cross-bracing inplace of infills. Cross bracing can consist of steel structural shapes or it can be accomplished by post tensioned cables. One should note that cross-bracing is not as effective as the infill in upgrading the lateral stiffness. It should also be pointed out that since cross bracing is made from steel, fire resistance will be a problem.

Since the lateral stiffness of infilled frames is very large as compared to bare frames, significant floor torsion can be created if such infills are placed without considering this effect.

One of the drawbacks of infilled frames is very large overturning moments being transferred to the foundation. If redistribution of such moments at the foundation level is not taken into consideration, the footing supporting the infilled frame has also need to be strengthened.

The most effective way of connecting the infill to the frame members is placing dowel bars into the drilled holes in the members. Bonding of dowel bars is usually accomplished by using epoxy based adhesives. Such a technique can be questionable when fire resistance is considered.

RELATED RESEARCH AT METU

In addition to uncertainties involved in estimating the seismic performance of an existing building, addition uncertainties are introduced due to rehabilitation. It is extremely difficult to estimate the stiffness and strength of repaired or strengthened members. Load sharing of added components such as jackets depends on many factors.

In the following paragraphs research done at the Middle East Technical University to understand the behavior of rehabilitated members and systems will be briefly discussed. Due to space limitations beam and slab rehabilitation will be left out (Ersoy, 1992).

Column Rehabilitation

Jacketed reinforced concrete columns were tested under uniaxial compression and combined bending (Ersoy et al., 1993). Following is a brief discussion of test results.

Columns Under Uniaxial Compression

The main variables investigated in uniaxially loaded columns series were the difference between repair and strengthening jackets (i.e. jacketing applied to damage and undamaged specimens) and jacketing made after unloading and jacketing made under load. Tests results showed that strengthened specimens by jacketing behaved almost as well as the reference monolithic specimen. Columns with jackets made without unloading behaved almost as well as the ones with jackets made after unloading. Based on the test results it was recommended to take the capacity of jacketed columns as 90% of the equivalent monolithic column.

Jacketing made to damaged specimens (repair) was sensitive to loading. The specimen with jacket made without unloading exhibited an inferior behavior as compared to the one made after unloading. It was concluded that if the jacketing to damaged columns have to be made under load, the contribution of the existing cross-section of the column should not be included in calculating the axial load capacity. Load versus strain curves of specimens tested are shown in Figure 2.

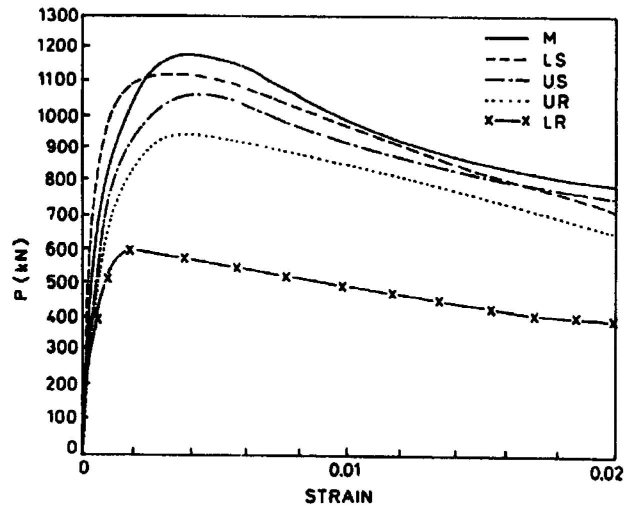
Columns Under Bending and Axial Compression

Five pairs of specimens were tested under combined axial load and bending. The test series consisted of jacketed columns and reference monolithic specimens. Both strengthening (undamaged) and repair (damaged) jackets were tested. In all cases jacketing was made after unloading. Specimens were tested under a constant axial load. The bending moment was increased at predetermined increments until failure.

Main variables in this series were; (a) type of jacketing (repair or strengthening) and (b) the load history (monotonic or reversed cyclic).

Specimens with strengthening jackets behaved almost as well as the reference monolithic specimens, both under monotonic and reversed cyclic loading. Repair jackets were made to damaged columns (crushing of concrete and initiation of longitudinal bar buckling). These specimens also behaved well. However their moment capacity was about 10 to 15 percent less than the capacity of the reference monolithic specimen.

Also the rigidities of columns with repair jacketing were about 25% less than those of the reference specimens(Ersoy et al., 1993).

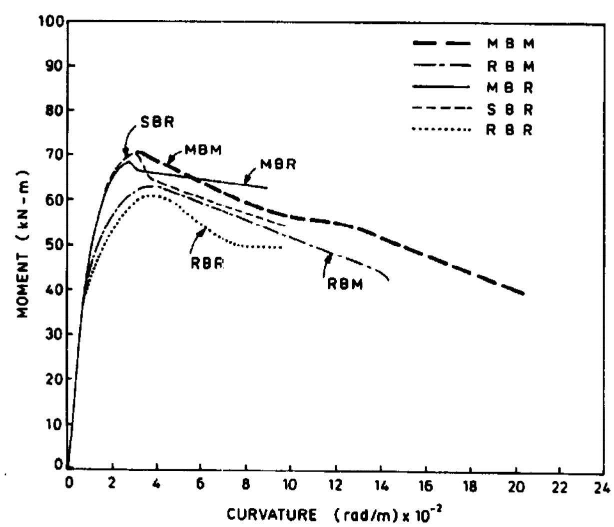


Legend:

M - monolithic reference specimen
US - strengthening jacket (undamaged) made after unloading
LS - strengthening jacket (undamaged) made under load
UR - repair jacket made after unloading
LR - repair jacket made under load

Fig. 2 Axial load-strain curves

To enable comparison, envelope moment-curvature curves of the specimens tested are shown in Figure 3.



Legend:

MBM - monolithic reference specimen - monolithic loading
RBM - specimen with repair jacketing - monolithic loading
MBR - monolithic reference specimen - reversed-cyclic loading
RBR - specimen with repair jacketing - reversed-cyclic loading
SBR - specimen with strengthening jacket - reversed-cyclic loading

Fig. 3 Moment-curvature envelops

In conclusion, it can be said that the deformation capacity and strength of existing columns (either damaged or undamaged) can be increased effectively by jacketing. However if the jacketing to a damaged column has to be made under load, only the jacket should be taken into consideration (disregarding the damage core) in computing the capacity of the jacketed column. In all other cases it would be safe to take the capacity of the jacketed columns as 90% that of the equivalent monolithic column. In case of stiffness, one should reduce this percentage to 75 (Ersoy, 1992).

The most important problems in column jacketing are the difficulties faced in providing continuity at beam-column joints and questions related to the joint performance.

System Improvement (Infilled Frames)

An experimental research project on infilled frames is being carried on at the Structural Research Laboratory of Middle East Technical University. The first phase of this work, where the infills were built in the undamaged frames has been completed and the results have been published (Altin et al., 1992).

Thirteen one-bay, two-story infilled frames and a reference frame have been tested under reversed cyclic loading. Frames of the first series were cast with low strength concrete (15 MPa) and there was no axial load on columns. Concrete strength of frames in Series-2 was increased to 35 MPa and the ratio of column longitudinal reinforcement was doubled. The frames of Series-3 were same as Series-2; however a constant axial load was applied to the columns. In each of the three series there was one reference specimen in which the infill and the frame were cast together (monolithic). The main variables investigated were; (a) reinforcement pattern of the infill and connection of the infill to the frame, (b) column axial load level, (c) concrete strength and (d) column capacity.

All of the infilled frames tested reached their ultimate flexural capacities. The final failure was sliding shear failure at the foundation level. Near ultimate load, separation of the infill from the frame was observed at frame corners. Observed behavior was almost linear up until 90% of the ultimate load. Increasing the column capacity by increasing the ratio of longitudinal bars increased the capacity of infilled frames. The presence of axial load on the columns had a similar effect.

All of the three different reinforcement patterns used for infills (grid, diagonal and concentrated reinforcement at the boundaries) were found to be satisfactory (Altin et al., 1992). Specimens in which the infill reinforcement was arranged as a regular grid, and connection was provided by dowel bars bonded into drilled holes in frame members behaved almost as well as the monolithic reference specimen. The envelope load-lateral displacement curves for specimens of series-3 are given in Figure 4.

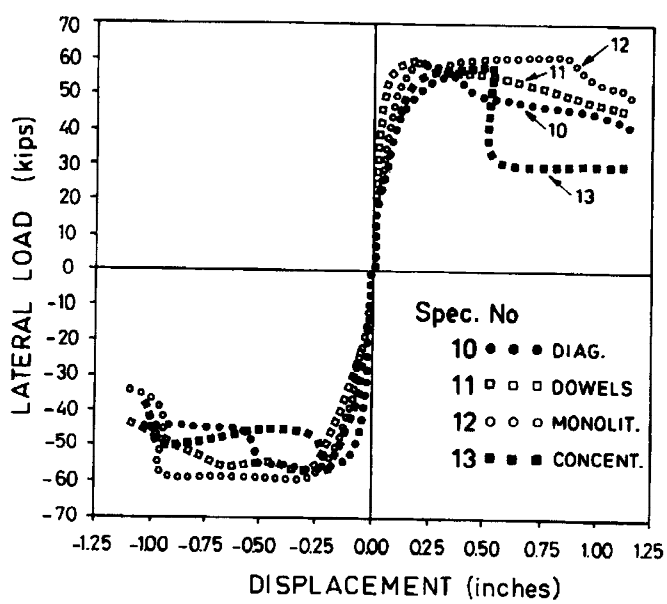


Fig. 4 Response envelopes - Series 3

Tests showed that both the strength and the stiffness increased significantly as compared with the bare frame. Ratios of base moment capacities of infilled frames to those of bare frames varied from 3 to 7. Ratios of stiffnesses varied from 10 to 40 (Altin et al., 1992).

In the test program discussed above, infills were added to undamaged frames. A new series of tests have just been initiated, where the infills are added to damaged frames. The members of the frames tested do not comply with ductility requirements of modern seismic codes (inadequate confinement and inadequate lap length) and the concrete strength used in the frames is low.

Some researchers recommend to strengthen the weak frame prior to infilling. Such recommendations are based on the assumption that the infilled frames have to behave as ductile walls. The writer does not agree with this approach. He believes that if adequate infilled frames are introduced, these frames together with the contribution of masonry infills will not permit the structure to sway beyond elastic limits. Therefore it would not be necessary to strengthen the columns.

CONCLUSIONS

Seismic rehabilitation has become one the most important concern in countries located in high seismic risk regions. Large investments are being made in this area and larger investments will be made in the future.

Although some research results are available, further research is needed to develop simple and practical methods for seismic evaluation of existing structures. Experimental research is also needed to understand the behavior of rehabilitated structures.

The writer believes that introducing structural walls or infilled frames is the safest and most practical way for rehabilitation. Research should be concentrated in this area.

REFERENCES

Altin, S., Ersoy, U., and Tankut, T. (1992). Hysteretic Response of R/C Infilled Frames. ASCE Structural Journal, v. 118, no.8, 2133-2150.

Ersoy, U. (1992). Repair and Strengthening of R/C Structures-Research at METU. International Symposium on Earthquake Disaster Prevention, Mexico City, v.2, 123-138.

Ersoy, U., Tankut, T., and Suleiman, R. (1993). Behavior of Jacketed Columns. ACI Structural Journal, v.90, no. 3, 288-293.

Hassan, A.F. and Sozen, M.A. (1996). Seismic Vulnerability Assessment of Low-Rise Buildings in Regions with Infrequent Earthquakes. Paper submitted to ACI Structural Journal.

Valluvan, R., Kreger, M.E. and Jirsa, J.O. (1993). Strengthening of Column Splices for Seismic Retrofit of Nonductile R/C Frames. ACI Structural Journal, v. 90, no. 4, 432-440.