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THE METHODOLOGY FOR THE SEISMIC EVALUATION OF EXISTING BUILDINGS AND COMPARATIVE ANALYSIS OF REHABILITATION OF STONE AND FRAME BUILDINGS IN ARMENIA

MICHAEL G. MELKUMIAN

Earthquake Engineering Center of the National Survey of Seismic Protection, Davidashen, IV Massive, 375054, Yerevan, Armenia

ABSTRACT

Different recommendations for seismic evaluation of existing buildings have been elaborated in Armenia in the past. But all of them were mainly directed to describe the present condition of the building without giving any quantitative estimation of its seismic resistance. The purpose of present paper is to generalize information in the field of seismic evaluation and to try for the first time in Armenia to develop the methodology for seismic evaluation of existing buildings. The goal was also pursued to compare different ways of buildings rehabilitation and to reveal their effectiveness.

The methodology is developed based on large scope experimental research studies, experience obtained resulting from the analysis of past earthquakes, international experience and the results of vibration tests performed for the full-scale buildings. Using the present methodology one should consider that it includes a number of assumptions. For this reason the methodology is providing an engineer with main directions and information relevant to the seismic evaluation of buildings. The main assumption resides in outlining the concept of earthquake resistance. Earthquake resistance is here taken to mean an ability to withstand seismic impacts given that stress-strain state of the building is limited to crack formation stage and possibility of plastic deformation development in the reinforcement is excluded during the entire period of building maintenance.

KEYWORDS

Seismic evaluation; earthquake resistance; existing building; way of rehabilitation; comparative analysis.

THE MAIN APPROACH OF THE METHODOLOGY

After the task of evaluating earthquake resistance of a building is set engineer's first step is to acquire all available information on the particular building. The documentation should include drawings, specifications, calculations, geologic and other relevant information related to the design, construction, maintenance and possible changes in the building during its operation time. These documents will be an important source of information used in the course of evaluation. In case the set of documentation is obtained engineer should acquaint with it in details before visiting the existing building. When visiting the building it is necessary to check up the compliance between the documents obtained and real situation as well as to collect supplementary information that is not reflected in these documents, but needed to evaluate earthquake resistance. Evaluating earthquake resistance it is recommended to follow the scheme given in Table 1. It shows all measures and decisions to be undertaken and approved in the course of evaluation. Principal comments to the suggested scheme are given below.

Table 1. Measures and decisions to be undertaken and approved in seismic evaluation

1	Are there drawings, calculations, specifications and documents on further modifications available?	Yes	Revision of available documents. Checking its correspondence to the actual building. Preparation of new drawings (if necessary) in order to refine the present condition of the building
		No	Inspection of the building in situ and preparation of drawings needed for carrying out seismic evaluation in its qualitative part
2	Definition of structural concept of the building and preparation of its design model	-	-
3	Definition of seismicity for an area where the building is located	-	-
4	Definition of physical, mechanical and dynamic characteristics of bearing structures of the building	-	-
5	Is there any additional information needed to implement quantitative part of seismic evaluation	Yes	Returning to the object in order to add drawings, test the materials, structures, etc.
		No	Estimation of A/R ratio
6	A/R > 1	Yes	Earthquake resistance of building is provided
		No	Implementation of the non-linear seismic response analysis of the building aimed at predicting its behavior under preset adverse earthquake accelerogram

In case the documentation on the building under evaluation is lacking the starting visit to the building has to include preparation of sketches on structural concept. These drawings should be prepared in sufficient detail in order to identify clearly a system resisting to vertical and horizontal loads as well as to carry out earthquake resistance evaluation in first approximation. Once the drawings on the building are examined and/or an engineer has performed initial survey of the building, design model of the building is to be prepared for applying it in seismic evaluation. In doing so structural features are to be described as a whole with consideration of the behavior of similar type structures in the past high intensity earthquakes.

After the design model is prepared engineer shall define maximum potential accelerations that will arise at the site of the building being evaluated. In addition to that all actual physical and mechanical characteristics of the building bearing structures are to be estimated. In doing so, collection of initial information for seismic evaluation of the building will be completed.

The A/R ratio (actual bearing capacity/required bearing capacity) is derived based on the collected initial information; non-elastic seismic response of the building is analyzed in case of need. Should additional information be required engineer has to return to the object whatever the stage of seismic evaluation procedure is. The additional information will be obtained in surveying the object in more detail, preparing more detailed drawings, testing construction material, etc. Non-structural elements should be investigated, too, and engineer has to evaluate their potential impact on the building earthquake resistance when defining the A. To conclude with, a report on seismic evaluation for the building should be prepared. The scope of details of the report depends on the task set by the client before the works are started.

INFORMATION COLLECTION PROCEDURE

Information collection presents one of the important parts of seismic evaluation for the existing buildings. The information acquired serves as a basis for the identification of a building and evaluation of its technical condition. However, information collection presents a procedure that is implemented not only at the start of seismic evaluation activities, but at its different stages as well, in case additional data are needed. The following issues may be sources for collecting information in seismic evaluation: a) design documentation, specifications, geologic engineering data and calculations; b) survey of technical condition; c) destructive and non-destructive testing of construction materials.

An overall set of construction drawings, which (if available) considerably simplifies and reduces the required scope of building investigation works, is the best information source. In addition to the main information about the structural concept of a building the drawings may contain data on the construction code according to which the design was implemented, as well as on soils and design loading. Specifications with the data on material properties and requirements to the quality represent other important information. Acts of concealed construction works should be collected to a possible extent in addition. Calculations made in designing the building shall be used in data collection as well. These calculations allow one to judge about the assumptions made in building design, the values of stories shear forces and bending moments. An engineer evaluating earthquake resistance may not initially consider the calculations until the separate response analysis itself is made. In case the parts of structure causing the greatest anxiety are thus revealed it is necessary to clarify whether they have been paid due attention when initial calculations were performed for the object. In all instances the results of available calculations should be compared first to the design documentation and then to the actual building. If any discrepancies are revealed the engineer shall try to evaluate their influence on the seismic response of the building. Finally, the data of geologic engineering study carried out in designing the building have to be used. The latter generally present reports including the data on site geology, availability of ground waters, seismicity of the territory and soil carrying capacity.

The engineer performing seismic evaluation should spare no effort to obtain as much design and construction documents on the object as possible, considering them as meaningful information sources. It is not infrequent, however, that this information is lacking, particularly for old buildings. If this is the case one can apply for assistance to local authorities, archives, house owners, historical associations, etc. to acquire any useful information.

Another most important step in collecting the information is in situ survey of the building technical condition. Number of visits and preciseness level depend on the completeness of information derived from design and construction documentation. Provided that the latter is complete enough it would be possible to visit the building only at the initial stage of seismic evaluation. Such initial survey should aim at refining the obtained design documentation and revealing its compliance to the real situation since any amendments and changes in the building would influence its seismic response significantly. The process of refining may require even uncovering of constructive junctions, joints and other parts given the proper permission. Another important evaluation element during the visit to the building resides in defining the condition of construction materials, whose properties are subject to deterioration under poor maintenance of the building. These are corrosion of reinforcement, concrete cracking and breaking off, etc.

In addition to the refining of technical conditions the initial visit to the site of evaluated building should help in collecting the following main information: a) name and/or address of the building; b) age of the building, any deviations or supplements; c) number of stories, their height, availability of cellars; d) position of neighboring buildings or structures; e) whether the building is under exploitation, who occupies it, whether its initial assignation is changed.

In the event that design and computational documentation is lacking or it is not complete, the larger survey of the actual situation is needed and sketch drawings have to be prepared. These drawings should include separate plans indicating location and dimensions of all bearing structures at all stories as well as whole of supplements or construction solidity violations. Other drawings should present vertical sections along all axes mentioning all of the openings, cracks and restorations of damaged sites if any. All changes in thickness, solidity as well as the sites with broken off concrete, corrosion of reinforcement and other impairing have to be indicated. It is needed to prepare sketches of standard and individually developed parts and units constituting the constructive system of the building.

The goal of implementing the above sketches and drawings is to provide an informational basis for seismic evaluation. This will help an engineer to acquaint with the building type and structural concept and save him the trouble of repeated visits to the building. Together with preparing drawings and evaluating technical condition of the building an engineer's visit should in situ include inspection of following items: a) availability of outer structures connected to the building; b) changes made in structural elements such as new openings or openings filled with masonry of different materials; c) structural link between different diaphragm-walls and horizontal diaphragms (floors) and vertical bearing structures; d) presence of stone fillings in the frames that does not hinder horizontal displacements of frame buildings; e) availability of parapets including their height , thickness, material, anchoring and position; f) presence of any components producing hazard and influencing seismic response of the building. The information collection should also involve the data on non-structural elements, namely: a) partitions, their type, material, way of fastening to bearing structures; b) hanging ceilings, their fastening ways and material; c) elevator shafts and constructions of stairs as well as the ways of their fastening; d) outer fencing walls, their fastening and material.

When visiting the building it is recommended to have: a) a camera with wide-angle objective; b) 10m tape measure; c) binoculars for observing hardly accessible structure sites; d) special ruler for measuring crack opening width; e) instruments for defining the strength of concrete; f) instruments for estimating protective concrete layer, location and diameter of steel bars; g) instruments recording oscillation period for the building and adjacent soils; h) diary or tape recorder to record the information.

METHODS OF TESTING

In addition to the consideration of design and construction documentation and performing survey at the site an engineer can obtain useful information testing construction materials and estimating natural vibration periods for the building. The scope of implemented tests depends on the type of construction material used for the structures, its homogeneity and identity, seismicity of the site where the building is located, scope of noticed damage and importance of structural elements. Testing of construction materials can be carried out with great use after preliminary analysis, based on which the most critical sites of the building as well as its dynamic characteristics are identified, is made.

Different ways for testing materials of building structures are known. Strength of the concrete for compression is usually estimated through testing a series of concrete cylinders taken from the body of existing structures and from their diverse parts. Non-destructive methods using different types of hammers, ultra-sound passage velocities, etc., are commonly applied. These tests shall not substitute testing of cylinders, however they allow accurate estimation of concrete strength and homogeneity.

Estimation of dynamic characteristics for the building and soils adjacent to it is significant. These characteristics can be defined under micro tremors, compared to each other and to the calculated values of building oscillation periods. Important conclusions about the state of the building and possible effect that a expected seismic impact may have on it could be drawn in doing so. Apparently, the building will appear in adverse conditions when affected by the expected earthquake if natural vibration frequencies of the building and adjacent soils are similar. This should be accounted for in seismic evaluation of the object. Besides, at the stage of intense plastic deformations the vibration period of a building is known to increase 1.5-2 times compared to the initial value. Consequently, if earthquake resistance of the building is estimated after it was subject to the expected seismic impact and the first mode vibration period of the building increased for not more that 30% one may conclude that the building disposes of sufficient strength resources. Such a building will resist possible earthquakes effectively after the reconstruction works are implemented. In case the building has not suffered an earthquake and its vibration period exceeds the expected calculated value for more than 30% a conclusion can be made that the building is not reliable and its earthquake resistance is not provided. Given an increasingly higher value of vibration period urgent measures are to be undertaken for evacuating the population. The vibration periods can be compared not only to the expected calculated values, but the periods of the same type buildings built in other regions or populated areas as well. In the event that vibration period increases after the expected earthquake 1.5 times and more it is concluded that this building is no longer capable to withstand seismic loading while its strengthening and reconstruction are not worth full economically.

ANALYSIS PROCEDURE

Quantitative seismic evaluation for the existing building is confined to the comparison of the actual bearing capacity A and the required bearing capacity R. Apparently, the A/R relationship should be equal to or higher than 1 for one to attest that earthquake resistance of the building is provided. Moreover, this ratio is to be checked up for each story of the building. Actual bearing capacity is a value of summary shear force at the level of each story, which can be felt by all of vertical bearing structures depending on their actual technical condition and actual strength of materials. The value can be defined for each story on the cross-sections of vertical bearing structures and their lateral reinforcement if any have been completely examined or, otherwise, this can be done according to the procedure described below. At the cost of the influence of non-bearing structures, which are known to display certain resistance to seismic impacts, the A values may be increased for 20% for frame structures, 10% for frame structures with shear walls and 5% for the structures with bearing walls.

The R is a value of total seismic shear force affecting each story of the building under the calculated impact. The R is defined through a calculation based on the Seismic Code effective in the Republic of Armenia at the moment when earthquake resistance of the existing building is evaluated. Definition of total seismic shear forces shall use the characteristics of construction materials provisioned in the building design. In case the engineer who performs seismic evaluation does not dispose of the building drawings the characteristics from other analogous building designs may be assumed. If the building has no analogs the characteristics shall be approved according to the recommendations of effective Code sections referring to constructive requirements.

It is very difficult to estimate for certain the number and diameters of reinforcement rods in bearing structure sections, if design information (detailed drawings) is not available for the building being evaluated. This significantly complicates the evaluation of the A and in certain cases makes it impossible. For this reason the following technique is recommended to estimate the A in the event that information on the building bearing structures is obscure First of all the strength of concrete for all vertical bearing structures of the building evaluated is to be defined in accordance with "Methods of Testing" section. Using valid normative documents the values of concrete elasticity modules are further established on the known concrete strength values. When physical and mechanical properties of the concrete for all bearing structures of the building estimated, the horizontal stiffness values for the latter are to be computed, using different known and approved methods as well as geometric dimensions of bearing structures taken from available drawings and defined as a result of in situ measurements. In case the horizontal stiffness is defined the following formula is recommended for the computation of the A of the particular story

$$A=K \cdot U \cdot (C_1+...+C_i+...+C_n), \tag{1}$$

where C_i is the horizontal stiffness of "i" vertical bearing element of the given story;

U is the ultimate displacement at the stage of linear behavior defined on Table 2;

K is a coefficient that is defined in Table 2 as well;

n is the number of vertical bearing structures.

Table 2. Data for computing the actual bearing capacity A for reinforced concrete buildings

Structural concept of the building	U	K
Frame with weak beams	h*/1250	4.5
Frame with strong beams	h/1500	4.2
Frame with solid shear walls or the structure with solid bearing walls	h/2000	4.0
Frame with shear walls or the structure with bearing walls having openings	h/3150	3.7

*) the height of story

The K and U values in Table 2 are obtained based on the analysis of large scope experimental studies of earthquake resistance of different types of reinforced concrete structures. These values may be refined as new data on the behavior of reinforced concrete structures under seismic loading are accumulated.

COMPARATIVE ANALYSIS OF REHABILITATION OF EXISTING BUILDINGS

After the disastrous 1988 Spitak earthquake the reconstruction of existing slightly damaged buildings has been started gradually. Taking into account high seismicity of the Armenian territory a problem arose related to the necessity of strengthening the existing buildings to reduce seismic risk of their collapse in future earthquakes. For this reason and in view of mass character of these works a need for comparing different methods of strengthening to reveal the most efficient, both from the standpoint of working technology and the cost of work implementation, came into being.

Different designs for the conventional strengthening of stone and frame buildings using reinforced concrete jackets and additional shear walls were developed. Somewhat later new unique methods that increase earthquake resistance of existing buildings by means of laminated rubber bearings (LRB) were created. The initiation of building strengthening activities became practicable due to the credit allocated to Armenia on the part of the World Bank for the earthquake zone reconstruction. In the framework of this project more than 25 buildings have to be strengthened using traditional techniques for the most. However, among these two have been expected to be strengthened applying seismic isolation structures. Mainly five-story stone and nine-story reinforced concrete frame buildings were due to strengthening. An average cost for the strengthening of one stone building comprised 300,000 USD, while that for one frame building was 150,000 USD. At the same time conventional methods are known to require evacuation of residents and providing them with temporary dwelling. This in turn requires additional expenditure.

Structural concepts intended to increase seismic resistance of the mentioned two buildings using laminated rubber bearings is proposed by the author of the present paper. One of them is a five-story stone building supplied with seismic isolation in its foundation part. Here the LRBs are step by step cut into the cellar story walls at the level of foundation upper edge through the creation of two-tier system of reinforced concrete beams. What is more. this is done without evacuation of residents. There has been no such a precedent in the world construction practice yet. For this building the price of strengthening comprised 170,000 USD that is almost 1,8 times cheaper compared to that for the traditional approach. Accounting for the cost of provided temporary dwelling in addition, the cost of the new way of rehabilitation will be more than two times less compared to the traditional one.

The second building is a nine-story frame structure, strengthened by means of an isolated upper floor (IUF) functioning as an dynamic damper of vibration. After the attic-story is dismantled an additional upper floor is constructed there, over the existing building, and connected to the building through the LRB. In doing so an isolated upper floor is created allowing for reduction of earthquake-related strain-stressed condition of the building. In this case the LRBs are for the first time in the world applied not in the building foundation, but in its upper part, on the contrary. This approach does not require evacuation of tenants as well and costs 70,000 USD, that is again more than two times cheaper compared to the traditional way.

All of the presented figures are completely real, since they have been obtained as a result of procurement and reflect contract prices for the strengthening of one or another building. Consequently, the new methods of strengthening are not only unique by their essence, but efficient either from the standpoint of their technical performance and behavior during strong earthquakes, or on the investment rate.

CONCLUSIONS

The methodology for seismic evaluation of existing buildings is developed for the first time in Armenia. It describes the steps required in performing seismic evaluation, the procedure of information collection, methods of testing and the procedure of building actual bearing capacity calculation.

A comparative analysis has been carried out for the stone and frame buildings strengthened conventionally and applying laminated rubber bearings. The application of seismic isolation to the five-story stone building and the use of isolated top story at the 9-story frame building allows to reduce the strengthening cost more than twice.