A New Approach for Earthquake Vulnerability and Damage Assessment of a Large Group of Existing Residential Buildings

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ABSTRACT :

This paper presents a new methodology for earthquake vulnerability assessment of a large inventory of existing buildings. It has been developed to meet the requirement for rapid, cost effective and reliable assessment of the capacities of the existing buildings, and to forecast the damages that may develop as a result of a given earthquake scenario. Vulnerability assessment of an existing building requires a lot of information regarding its structural system. In most cases there is not enough available data, if any. Collecting the required information for a large group of buildings is time consuming, expensive and therefore impractical.

An engineering-rationale based approach is developed to confront with this task. The buildings topology gained from GIS databases, is carefully examined in light of additional supporting data related to local historical development, applicable codes, etc. Using this data, a "most likely" structural system is composed. This procedure can be carried out over a large inventory of buildings and serve as a base for the following structural analysis, in order to estimate the capacity of these buildings.

The algorithms are integrated in a GIS database, to enable the "automatic" examination of large inventories of buildings. Implementation of the proposed approach that shows its potential has been conducted in a small town containing 1600 houses.

KEYWORDS: Vulnerability, Assessment, Buildings inventory, GIS, Topology.

1. Introduction

In earthquake prone areas there is a need for the assessment of the capacities of large numbers of existing residential buildings. The results of such assessment are essential for rational planning of retrofit programs for existing buildings before the occurrence of a strong earthquake, for the allocation of rescue forces and equipment to optimally deal with the forecasted damage, etc.

Unfortunately, existing residential buildings are poorly documented and the available data concerning their structural properties is very limited. Reliable Assessment actions require comprehensive information regarding the buildings structural systems, including configurations and dimensions of their structural members, structural and non structural details, material strengths, etc, prior to the implementation of any analysis procedure, even if it is a relatively simple analysis. If retrofit is considered for an individual building, then its capacity analysis should be based upon a systematic study of this specific building and supported by technical documentation and adequate testing. However, extending these methods to a large inventory of buildings requires vast efforts of data collection, as well as analysis, making these assessment procedures impractical for widespread, or large scale general use. For these reasons, such large scale assessments are presently based on statistical brief evaluations of these buildings through adopting side walk inspection procedures, or upon the assignment of general pre defined representative fragility curves, as is done for example by the HAZUS code (HAZUS®99). One might ask if it is feasible at all, to develop a fast, reliable enough and cost-effective engineering method for earthquake vulnerability assessment of buildings that will be suitable for large inventories of existing buildings, and not rely upon statistical data only.

In recent years Geographic Information Systems (GIS) are frequently used in many engineering applications. There were some attempts (e.g. Miura, 2004. Sousa, 2004) to propose the usage of part of the building information incorporated in existing GIS data bases also for earthquake vulnerability assessment purposes. However, this usage is mainly based on coarse division of the buildings inventory into certain categories, for example according to the age of construction, type of construction, structural materials, height of the buildings, etc., and not upon a systematic engineering method, utilizing the entire existing data base, to reach a more comprehensive knowledge regarding large inventories of existing buildings.

In the present research, a new engineering-rationale based approach is developed, to confront this challenging task. The proposed approach is based on a very limited amount of available data that is included in common GIS databases, such as coordinates of the corners of the buildings footprint, from which the polygonal shape and dimensions of the buildings floors layout are derived, as well as the elevation records of the buildings roofs and ground, from which the overall height of the buildings may be determined. Additional needed data are derived from thorough examination of the topology of the layout of the buildings in light of special characteristics of the buildings inventory.

Buildings inventory is not just an arbitrary collection of various building shapes. Different groups of buildings are developed and built in the context of historical, political, economical and social processes, related to the development of a state or a region, and are related to the changes in the population, in the life style, in the architectural regulations and applicable design codes. This development is mainly made by intended policy, as part of local historical processes. For these reasons it is possible to relate a series of relevant architectural and structural features and details to a typical construction era or location. When this information is gathered and formulated in a series of logical connections, formulae and laws, it may serve as part of the data base and provide us with essential supporting data. This additional data complements the initial limited database and may help in the process of deriving the scheme and shape of the "most likely" structural system of the building. It should be noted that the "most likely" scheme is derived in the presence of limited data and many unknowns. Therefore it is not likely to be identical to the real structural system of the building under consideration. It is in fact an apparent structural system that is defined and assessed on the basis of limited available data and complementing assumed data, defined on the basis of available sources of information and best available engineering judgment.

Once the "most likely" structural system is determined, it can be analyzed by common techniques to evaluate its resistance and assess the potential damage that will occur due to a given earthquake. This presentation is focused on the first part of the process aiming at formulating the "most likely" structural system.

A brief description of current assessment methods is given in section 2. The proposed approach is presented in section 3. Section 4 describes several examinations that were carried out with the proposed methodology based on the GIS data base of a small Israeli town containing 1600 buildings.

2. Assessment of available methods

Most of the existing evaluation methods refer to a single building, among which we may find: methods that are based on statistics of past EQ damage records (Whitman, 1974), methods that are based on experts subjective opinion (ATC-13, 1985. FEMA 178, 1992. EMS 1998) methods that are based on score assignments of predefined checklists exposing structural deficiencies that do not contain even elementary engineering calculations (FEMA 154/5, 1998. NRC-CNRC, 1996. NZSEE, 1996. I.S 2413, 2003), simple analytical methods to simulate buildings response that are essentially simple approximate solutions that must rely on a few parameters (ATC-14, 1987. Calvi, 1999. Priestley, 2003) and detailed analytical procedures (ASCE 41-06, 2007) which are more accurate but require much data and are time-consuming.

The reliability of these methods differ considerably, from limited reliability of the simple statistical and rapid screening methods, to the most reliable methods that are based on detailed analytical procedures that may evaluate the mechanical behavior of the structural system under consideration, but require an enormous amount of data, that is commonly not available, and take much time in their processing.

In order to get a rough estimate of the required time for a minimal assessment of a single building, we compared 3 different existing approximate approaches (the Israeli code I.S 2413, 2003 for preliminary rapid assessment, FEMA 154, 2002 for side walk inspection, and ASCE 31-03, 2003, for simple analysis). The results are shown in **Table 1**. These methods are based on the observed data on site without any or very limited further search or investigation, and therefore suffer from limited accuracy. It turns out that using these methods, even the simplest and least accurate ones, requires tens or even hundreds of man years for an approximate evaluation of the earthquake resistance of all residential buildings in a moderately large city. Extending these results over the entire country becomes at least an order of magnitude larger. Clearly these Figures make these options impractical for the assessment of a large inventory of buildings.

Table 1.Time estimates of different approximate assessment methods

	Method of Assessment Time estimates	ASCE 31-03	FEMA154	IS 2413
A	Time for 1 person (in a group of 2) required to collect data for a single building	~2 hours	~ 1 hour	~ 0.5 hour
B	Time required for resistance assessment by an experienced structural engineer	~3 hours	~0.5 hour	~0.25 hour
C	Total time required for assessment of a single building by 3 team members (C=2*A+B)	~7 hours	~2.5 hours	~1.25 hours
	Total time required for the assessment of 10,000 buildings	**~ 30 years**	**~ 11 years**	**~5.5 years**

3. The proposed Approach

The proposed approach aims at developing of a rapid GIS based technique for assessing the structural systems of a large inventory of residential buildings, where only limited data is available. There is need for much more data in order to come up with the "most likely" structural scheme of a building that will enable its analysis, and this data is derived from logical procedures that are based on several data bases. The proposed methodology makes an attempt to produce the information from a "distance", namely without the need to search for the buildings documents, or conduct site visits to check and document the buildings, or perform any measurements or tests whatsoever. The entire work is done in the office by a computerized set of algorithms, with automatic decisions based on pre-defined rules, at a very short time and with minimal time resources compared to all other alternatives.

It has already been mentioned that only a modest amount of information is available in the GIS database. In Israel it includes location of the buildings, nodal coordinates of the buildings footprint polygon, absolute ground and roof elevation, year or decade of construction and building usage. This set of data is the starting point of the following procedures.

If the nodal coordinate data would have been printed out, we could see a set of closed polygons, mostly of right angles, representing the contours or footprints of the different buildings. As we deal with a computational algorithm and not with personal processing procedures, we have no need of printing out the data, but process them along with given algorithms. Examination of the nodal coordinates set of many buildings yield the following observations: Most buildings' footprint is characterized by parallel and perpendicular sides, and its vertices are either ~90 degrees, (convex) or ~270 degrees (concave). Many polygons have a simple rectangular shape with 4 sides; the others mostly have an even number of sides. Classification of all the polygons according to the number of their sides shows that only a small number of polygons have more than 12. To obtain a more quantitative appreciation of the polygons distribution function, a small Israeli town with about 1600 residential buildings was examined.

It was found that more than 60% of the residential buildings have rectangular shapes, and the distribution of the rest of them is: 9% with 6 sides, 10% with 8 sides, 4% with 10 sides and 6% with 12 sides. The cumulative distribution shows that this set of shapes, of up to 12 sides per polygon, represents about 90% of the entire residential buildings inventory. Although this finding refers to a specific town, and more studies should examine the distributions for other cities, it indicates that footprint polygons are rather simple with a limited number of sides, and more complex shapes are rare. As most of the polygons have an even number of sides, it may be concluded that polygons with 4, 6, 8, 10, and 12 sides are sufficient to represent the entire inventory of buildings.

A following study of the geometrical properties of a polygon with right angles between adjacent sides shows that a 4 sided polygon yields a rectangular shape, and a 6 sided polygon yields a "**L**" shape. Higher order polygons may have more than one typical shape. Further geometrical study of the different polygons geometrical properties (Yankelevsky et al, 2008) shows the following: an 8 sided polygon has 4 different possible shapes, a 10 sided polygon has 8 different possible shapes and a 12 sided polygon has 31 different shapes. In total the representative polygons of 4,6,8,10 and 12 sides have 45 different shapes. It turns out that theoretically 45 different shapes are sufficient to describe all possible right angle polygons having up to 12 vertices, and cover about 90% of the entire residential buildings inventory. In practice the actual number of buildings' layout is even smaller, because of architectural constraints and design considerations of the layout of a residential building's typical floor.

Analysis of the possible shapes is needed to understand the geometrical shape of the polygon in order to determine the floor's geometrical design and its division into apartments, to determine the possible location of the staircases shafts, to assess where is the possible location of separation joints, to determine the location of partition walls etc. Most of these data are not included in the GIS database and logical procedures that follow these considerations are essential to this process.

When the possible building's floor layout polygon shape is determined, the floor area may be subdivided into dwelling units. If the number of dwelling units per floor is given, the task is relatively simple. Otherwise a series of considerations and estimates should take place.

Firstly, we determine the length L and the width B of the floor layout ($L \geq B$), and calculate the total floor area A. A common GIS database does not contain data about the overall number of dwelling units in residential buildings, or the number of dwelling units per typical floor of these buildings. Therefore it is necessary to have a rough estimate of a typical dwelling unit area, with aid of which, the number of dwelling units per floor can be determined. Over the years the dwelling unit's area has been increased gradually. An historical survey has been conducted to determine the gradual changes of the average sizes of dwelling units over the years in Israel. It is based on three different sources (architectural surveys and an official report of the Central Bureau of Statistics) and may provide a reasonable tool to make an assessment. According to these data, the dwelling unit's area varied during the years, since the establishment of Israel, from 53 sq.m to127 sq.m. approximately. When the year (or decade) of construction of the building under consideration is documented in the GIS database, as is commonly the case, then the corresponding representative average dwelling unit area may be predicted. Otherwise, an average value may be assumed.

The floor geometry together with the built up information about the different dwelling units in the floor, gather the major components for assessing the shape of a typical floor design. Based on that data, and considering the building height and total assumed number of dwelling units, we can assess the number and size of staircases and elevator shafts and place them in the most likely location within the floor layout. Different rules are built up for the assessment of a dwelling unit's shape, and its place in the floor geometry, as well as for the different shafts, that are beyond the scope of this paper.

When the entire layout of the floor is determined, we can assess the location and number of expansion joints. Expansion joints are used in relatively long buildings to allow contraction and expansion with limited strains due to fresh concrete shrinkage, hardened concrete temperature deformations, etc. An expansion joints subdivides the structure into substructures and the group of substructures may behave in a significantly different manner than the single complete structure, both under static and under dynamic loading conditions. In the latter case, we may mention possible pounding of adjacent buildings or substructures that are separated by a narrow joint, during earthquakes. The occurrence of pounding may induce extreme impact loads that commonly lead to catastrophic results. During the years regulations and measures of good practice instructed to introduce expansion joints when the length of a building exceeded a certain measure. This measure varied with the years, as a result of experience, technological developments and changes in design standards. These distances increased during the years, resulting in fewer expansion joints in newer buildings, compared to older ones. It is a common practice that in residential buildings expansion joints usually do not cross a dwelling unit but are placed between adjacent dwelling units. Recording the data and common practices with that regard along the years builds the data base that helps to determine the most likely number and location of expansion joints in a given floor geometry of a residential building, when its year of construction is known.

From the GIS elevation data of top point of the building and the elevation data of the local ground surface we can estimate the number of floors. This is also based on a review of data and regulations along the years that help to build up the rules for the determination of minimum and maximum expected net height of a dwelling unit and of a ground story. Common spans in residential buildings and types of floors may lead to the estimate of the floor thickness and hence to the gross floor height.

The number and dimensions of staircase shafts and the criterion for the number and size of elevators depend on the number of stories. The Israeli building code determines the requirements regarding staircase shafts and elevator shafts in a given building, depending on the height of the building and the number of its stories. It also specifies the major dimensions (cross section area, openings, etc.), allowable construction materials, etc., regarding these shafts. These requirements lead to common solutions that may be accumulated into a library of typical staircase and elevator shafts that can be incorporated into the evaluation procedure.

Conventional construction of reinforced concrete skeletons with infill masonry walls and partitions is very common for residential buildings in Israel. The masonry walls are mainly made of either hollow concrete masonry units or autoclave-cured aerated concrete blocks. The exterior walls and the partition wall between adjacent dwelling units are usually made of 20 cm. thick masonry infill walls and the interior partition walls of a dwelling unit are usually made of 7-10 cm. thick masonry walls. Although the masonry infill walls are not considered as structural elements and usually are not taken into account in the analysis of the buildings resistance, they do affect both the buildings stiffness and its capacity. Therefore, they should be taken into account in estimating the capacity of existing residential buildings to resist earthquakes, especially masonry infill walls that are at least 15 cm thick. This paper is focused on the estimation of the "most likely" structural system, to enable its following analysis, and these data may be used in the capacity analysis.

Once the floor layout geometry is fully determined and some of the vertical components of the building were defined and placed in their most likely position, such as elevators and staircases shafts, the columns system may be determined. The possible location of the columns is determined on the basis of architectural considerations and commonly used floor spans. Columns size prediction is assumed only for gravitation loads as was typically done in the past. Common types of concrete used in construction of residential buildings (uniaxial compressive strength of 20-30 MPa) are assumed, in order to enable the assessment of the columns cross section dimensions, as a function of the relative floor area carried by each column and the number of supported stories, which affect the total gravitational load carried by the columns.

Architectural and structural considerations may yield different solutions to the same problem and provide different possible columns arrays with their corresponding cross section areas, for the same building. Increasing the spans may yield less columns with larger cross section areas and vice versa. Thus it is almost impossible to predict the "most likely" array of columns that will be identical to the "as built" columns array of the same building. However, there is much in common to all possible column arrays of the same building, as they should carry the same total gravitational loading. Since our goal is to come up with the "most likely" structural system in order to get a realistic assessment of the buildings capacity, it is not essential to get identical columns array and close enough arrays may yield similar results with regard to the buildings capacity. In order to get close estimates for the floor spans/tributary floor areas of columns, it is helpful to rely on data of common spans that have been used for residential buildings throughout the years.

The foundation system of existing residential buildings depends on local soil conditions. In locations where the foundation soil is granular (sand, gravel, sandy clay), or rock (limestone, dolomite, granite) shallow spread foundations are usually applied as columns footings and continuous strip foundations for reinforced concrete, or masonry load bearing walls. In locations where the foundation soils are clay, or sandy clay, usually deep reinforced concrete pile foundations are applied. Therefore, the type of the foundation system of an existing building can be assumed with a high degree of reliability, provided the local soil conditions are known. It should be noted, that information regarding the local soil conditions is necessary also for defining the expected seismic loading of a given structure in case of an earthquake of a certain magnitude. Presently there are GIS based databases regarding the expected horizontal ground accelerations at the bedrock level, at different locations of the country (in terms of global coordinates of the various locations). However, information on local geotechnical soil conditions is not incorporated into the existing GIS database and this database should be further developed accordingly.

Once the structural system's geometry is determined, its different components may be examined from the structural point of view. Preliminary analysis may assess the most likely reinforcement data, taking into account structural data and reinforcing details that were common or effective, based on relevant standards and codes of practice, depending on the period of construction. A detailed library of data was prepared to support the assessment of the structural details of the most likely structural system.

Once the structural system has been developed to this stage of full most likely geometry and full reinforcing data, it is ready for any structural analysis, including the capacity estimate to lateral loads and the response to any earthquake excitation. The structural analysis may be carried out by common available techniques and is beyond the scope of this paper.

Examination of the proposed methodology

Several studies have been made on buildings in a small town in Israel in a mountainous area. Most of its residential buildings, as is quite typical all over Israel, were built during the last 60 years. There are some 1600 low to moderate height (up to 8-9 stories) residential buildings in this town. In the first stage of the research a group of buildings was arbitrarily selected in order to implement the methodology's procedures and then conduct site visits in order to document and compare the real data with the predicted data. Comparisons were done between the estimated values established according to the present methodology and the real values of the examined buildings. The following parameters were compared: the number of dwelling units per typical floor, the number of expansion joints and the number of stories in the building. The comparison shows good predictions, with a limited number of discrepancies, that are related to several reasons among which are: uncommon distance between expansion joints in one building, mistaken data in the basic GIS database regarding the height of the building in another building, and in another building we found out that retrofit of the building was carried out long after its construction and added a new wing thus adding significantly to the dwelling unit area. These discrepancies can not be predicted, however they are exceptional compared to a very good correspondence of all other examined buildings.

Passing this stage of comparison, we selected several buildings for a more detailed comparison of their predicted "most likely" typical floor layout with the real floor layout. **Figure 1** shows a comparison of the predicted "most likely" layout of a building having a rectangular footprint with the real floor layout as obtained later from the original drawings of the building and verified during a site visit.

It was correctly predicted that this is a 6 story building. In this case the prediction of the number of expansion joints was inaccurate. **Figure 1** shows the predicted, "most likely", floor layout including all major components of staircases, walls, columns, etc. It was predicted that the building has an open ground story and a later site visit confirmed this assessment. **Figure 2** shows the real floor layout of the same building. It seems that the predicted layout is very close to the real layout, although some deviations are observed. One may observe a difference in the location of the staircase shaft and slight differences in its geometry between the two versions. There are some differences in the columns locations and in their cross section areas, however the differences are rather small and towards a more conservative evaluation of the building's capacity, on the basis of the "most likely" layout.

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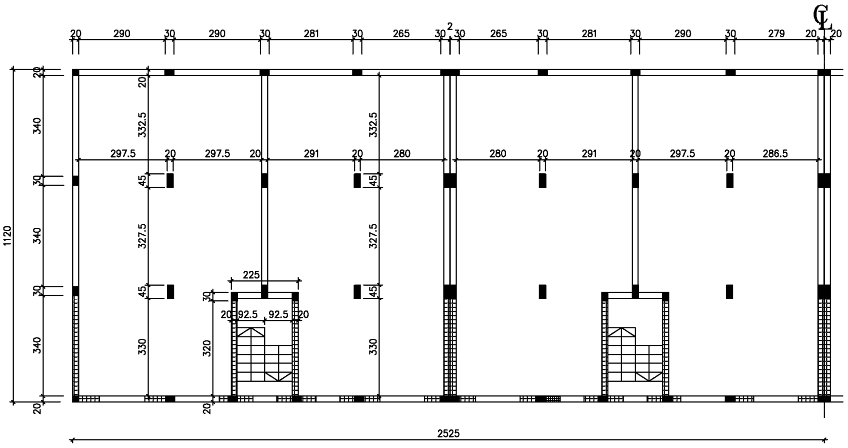

Figure 1. Assumed "most likely" layout of half ground floor of a 4 sides polygon building whose real layout is shown in Fig.2.(Yankelevsky, Schwarz, Offir, 2008).

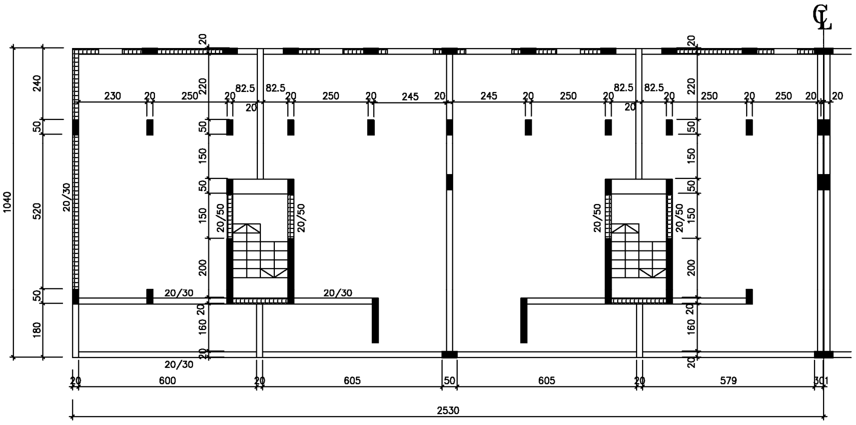

Figure 2. Real layout of half ground floor of a 4 sides polygon building. (Yankelevsky, Schwarz, Offir, 2008).

Summary and Conclusions

In this paper the basics concepts of a new methodology for creating a database for efficient earthquake capacity assessment of a large group of existing residential buildings is presented. It starts with a very limited (GIS) database, and is expanded on the basis of additional data derived from the buildings topology and other developed data bases related to local historical development, regulations, practices etc. Engineering-rationale based algorithms are then derived and used to process this set of data, as shown in the paper, to finally compose the "most likely" structural system of each one of the buildings.

Currently these algorithms are used to create computer software in order to predict essential structural parameters of a large inventory of residential buildings, to enable further processing and prediction of their capacities to resist lateral loading.

The present methodology deals with existing residential buildings and can be extended to other types of buildings. The algorithms are integrated in a GIS database, to enable examination of large inventories of buildings. It should be noted that although the present approach is quite general, its quantitative parameters are based on local conditions, trends and history of architecture and construction in Israel. Its implementation aims therefore towards residential buildings in Israel. The authors believe that the approach can be rather easily adapted, if carefully used, to other countries and other types of buildings.

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