International Journal of GEOMATE, April, 2018 Vol.14, Issue 44, pp.134-141
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.44.85087
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

VULNERABILITY ASSESSMENT OF RESIDENTIAL BUILDINGS IN JEDDAH: A METHODOLOGICAL PROPOSAL

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ABSTRACT: The City of Jeddah in Saudi Arabia is expanding rapidly, in terms of new buildings and increasing population. The rapid urbanization leads to higher risk from seismic events; even in areas of moderate seismicity such as this city. The present study addresses the rapid evaluation of a large number of buildings in Jeddah involving steps to determine hazard, assessing building stock, and computing vulnerability with a scoring method from FEMA 155. Two districts were selected for investigation based on a cluster analysis applied to population and building data from the local municipality. One selected district was a contemporary developed urbanized area, and the other was a more traditional area. Such selection offered the possibility to compare vulnerability of buildings built according to different seismic codes and to make assumptions about the rest of the city based on typical structures of districts. The basic structural score was determined considering the building structure and moderate seismicity of the region using score modifiers, e.g. vertical irregularity score modifier; soil score modifier assuming sabkahs. The results of the investigation reveal a different level of vulnerability and areas where intervention is needed. The method can be applied for further analysis of the city.

Keywords: Jeddah, Visual screening, vulnerability, Earthquake risk

1. INTRODUCTION

The City of Jeddah in Saudi Arabia is expanding rapidly lately in terms of buildings and population. The increased development and urbanization means a higher seismic risk; even in areas of moderate earthquake hazard such the area of present investigation. Present study specifically addresses the rapid evaluation of large number of buildings in the city with steps of assessing building stock, and computing vulnerability with a scoring method.

Research in earthquake hazard mitigation has focused on evaluating potential building damage scenarios from different magnitude events, prior to such an event. These methods facilitate prevention by gathering information about the state of the building stock and the expected damages, so authorities can strengthen the most vulnerable buildings in order to mitigate risk.

Since many of the buildings are too irregular and have a wide variety of material properties, comprehensive structural analysis and evaluation become too time consuming when considering thousands of buildings. Instead, alternate methods of evaluating building vulnerability have been applied in many places and provide a reasonable compromise of time, cost and efficiency. Visual classification systems developed by researchers and agencies are largely based on inspection of structural systems, time and mode of construction, and materials used.

Evaluating buildings by Rapid Visual Screening (RVS) requires less expertise and time for each structure. Instead of several buildings evaluated, hundreds or thousands of structures can be compared, classified, and evaluated. As a pre-earthquake assessment tool, score assignments from RVS may be used to evaluate the relative vulnerability of structures in the same vicinity. This study adopts methods of previous research and interprets score assignment values of FEMA 155 [1] to the buildings in Jeddah.

2. ASSESSING THE VULNERABILITY

Calvi (2006) emphasizes that for vulnerability assessment "*One of the main ingredients in a loss model is an accurate, transparent and conceptually sound algorithm to assess the seismic vulnerability of the building stock and indeed many tools and methodologies have been proposed over the past 30 years for this purpose.*" [2]

In case of analytical approaches, the vulnerability is expressed as the critical acceleration causing a damage mechanism to occur based on identification of collapse mechanisms, yielding the equivalent shear capacity [3]. Detailed analyses are time consuming and these evaluations correspond to the methods of structural analysis and design. The main disadvantage is that they should be performed for every investigated building individually, so alternative methods have been developed to enable the rapid evaluation of large building stock.

Visual screening methods, based on systems calibrated by experts, allow for the quantification of structural vulnerabilities more easily than analytical approaches. There is no need for detailed calculations and multiple scenarios. In the case of observed vulnerability [4], [5] the damage is defined as a ratio of the replacement cost or the degree of loss of all affected buildings considering as well the number of casualties. The relation between damage and earthquake intensity is valid only for the region where it was developed. Another method is to ask experts to estimate the expected percentage of damage caused by a given intensity, which are implied in macroseismic scales, e.g. European Macroseismic Scale (EMS) [6]. These scales are used to evaluate the possible damages after an earthquake [7].

Score assignment methods are determining seismically hazardous structures by identifying structural deficiencies. Quantitative information are gathered to determine the level of damage according to the severity of a potential seismic event. Potential structural deficiencies are identified from observed correlations between damage and structural characteristics. The main aim is to determine if a particular building needs a more detailed investigation or not. Score assignment methods have been successfully applied recently to seven European cities in the RISK-UE European project [8]. In Japan, the JBDPA (Japanese Seismic Index Method) describes three seismic screening procedures to estimate the seismic performance of a building: a seismic performance index (strength, ductility, etc.), time-dependent deterioration of the building and a seismic judgment index for safety of structure [9].

3. THE CONSIDERED RVS METHODS

The RVS method, based on visualization and scoring, can be used for ranking a community’s seismic rehabilitation needs; designing seismic hazard mitigation programs for a community; developing inventories of buildings for use in regional earthquake damage and loss impact assessments; planning post-earthquake building safety evaluation efforts; and developing building specific seismic vulnerability information for purposes such as insurance rating, decision making.

The RVS method relates common building structural, material and construction features to seismic building capacity curves. It is also known as push-over curve, which is a plot of a building's lateral-load resistance as a function of some characteristic lateral displacement. It is derived usually from static push-over analysis that defines the relationship between static equivalent base shear versus a building's roof displacement. Standard building capacity curves for different classes of buildings have been developed from many possible combinations of structural systems and materials.

Generally, it is assumed that the final push-over state corresponds to building collapse, or ultimate limit state. The capacity curve of the building is compared to the demand spectrum corresponding to low, moderate or high demand seismic event. Depending on the relation between capacity (resilience) of the building and the demand (intensity) of the seismic event, the building will have some probability of collapse. A low capacity with high demand will generate a high probability of collapse, while a high capacity with low demand will generate a low probability of collapse.

The commonly used RVS methods by EMS and FEMA 155 do not require the user to perform any structural analyses. Instead, the evaluator must collect data and determine the following:

- identify the primary structural lateral-load-resisting system, add basic structural score;
- identify building attributes that modify the seismic performance expected of this lateral-load-resisting system, such as: applied code, height, building irregularity, and soil conditions.

In order to complete the evaluation process, a wide variety of data is needed. Once collected, the different data sets are classified (grouped) into one of many (perhaps as many as ten) categories. An essential step in risk analysis is to ensure uniform interpretation of data and results. When dealing with vulnerability models, the classification system should group together structures that would be expected to behave similarly during an earthquake.

Table 1 Vulnerability table of EMS [6]

Type of Structure		Vulnerability Class					
		A	B	C	D	E	F
Masonry	rubble, stone, fieldstone	O					
	adobe (earth brick)	O	—				
	simple stone	- -	O				
	massive stone		—	O	- -		
	unreinforced, with manufactured stone units	- -	O	- -			
	unreinforced, with RC floors		—	O	- -		
	reinforced or confined			- -	O	—	
Reinforced	frame without earthquake-resistant design (ERD)	- -	- -	O	- -		
	frame with moderate level of ERD		- -	- -	O	—	
	frame with high level ERD			- -	- -	O	—
	walls without ERD		- -	O	—		
	walls with moderate level of ERD			- -	O	—	
	walls with high level of ERD				- -	O	—

The EMS offers a simple differentiation of the resistance of buildings to earthquake-generated shaking (vulnerability) in order to give a robust way of determining how the buildings may respond to earthquake shaking. The Vulnerability Table (Table 1) categorizes in a manageable way the strength of structures, taking both building type and other factors into account such as state of the buildings, quality of construction, irregularity of building shape, level of earthquake resistant design (ERD), etc. Subdivision of structures marked with letters from “A” to “F” were determined roughly based on different levels of vulnerability and not based on an architectural point of view. For each building type, the vulnerability table gives a line showing the most likely vulnerability classes, and also the probable range shown as a dashed line. The position of a particular building along this line has to be found by considering other factors contributing to the building’s vulnerability.

Damage grades from 1 to 5 represent the increase of shaking describing classes of damage, which can be easily distinguished.

FEMA offers also a RVS method providing an approach to classify surveyed buildings into two categories: those acceptable as to risk to life safety or those that may be seismically hazardous and should be evaluated in more detail by a design professional experienced in seismic design. For classification purposes the seismic-lateral-load-resisting system of buildings should be identified (Table 2).

Table 2 Building classification of FEMA 155 [1]

W1	Light wood frame residential and commercial buildings smaller than or equal to 5,000 square ft.
W2	Light wood frame buildings larger than 5,000 square feet
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frames with cast-in-place concrete shear walls
S5	Steel frame buildings with unreinforced masonry infill walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear wall buildings
C3	Concrete frame buildings with unreinforced masonry infill walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM1	Reinforced masonry buildings with flexible floor and roof diaphragms
RM2	Reinforced masonry buildings with rigid floor and roof diaphragms
URM	Unreinforced masonry bearing wall buildings

According to FEMA, the probability of collapse is represented by a Basic Structural Hazard Score (BSH) represent the average probability of surviving a seismic event, the maximum considered earthquake (MCE) in Eq. (1). The BSH scores are estimated from the building fragility and capacity curves of the HAZUS Technical Manual [10]; representing an "average" score for buildings in each class used for large-scale economic studies.

$$BSH = -\log 10[P(collapse\ given\ MCE)] \qquad (1)$$

Additional building features, so called Score Modifiers (SMs) specific to that building may increase or decrease the BSH score resulting in the final Structural Score (S) in Eq. (2).

$$S = BSH \pm SMs \qquad (2)$$

4. APPLIED RVS METHOD IN JEDDAH

Taking into account the advantage of score assignments with respect to observed data or expert opinions, namely that it allows for updating following a modification to the building structure, RVS was chosen for the case study carried out in Jeddah city.

For masonry buildings, EMS classification considers seven typologies, various materials, techniques of installation and construction particulars. FEMA classifies masonry structures according to reinforcement only. The detailed EMS classification was not needed in this research because this type of building in Jeddah would fall into the category of “unreinforced masonry” regardless of its other features.

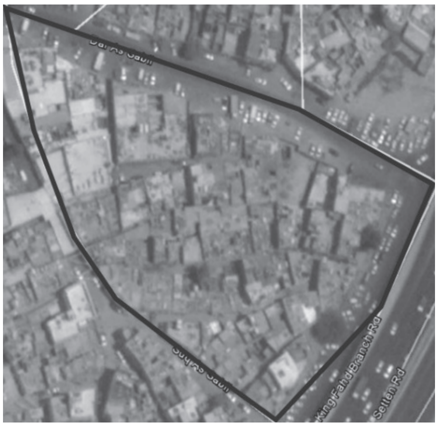
For reinforced concrete structures (RC) EMS differentiates the construction only in relation to the seismic resistant system (frame or shear wall). But FEMA also determines one more category for RC: concrete frame with unreinforced masonry infill, which is typical to this region as well. These differences favored the use of FEMA for this study tailored to the most-used building construction of the area.

Two districts were selected for investigation based on cluster analysis taking population data and building number collected from the Municipality office (Fig. 1). The objective of the survey was collecting physical information on residential buildings in two districts in Jeddah. One of the districts represented a developing urbanized area: Al-Salamah; and the other one was a typical old area: Al-Balad. This selection offers the possibility to compare vulnerability of buildings built according to different seismic codes and to make assumptions about the rest of the city based on typical structures of districts.

Most of the collected data was taken from Al-Salamah district as Al-Balad was having more commercial buildings than residential (Table 3). Moreover, Al-Balad is considered a historical area so most of the buildings were unoccupied (Fig. 1). In Al-Salamah district most of the buildings are following the same structure and using same material as it is enforced by Municipality.

Table 3 Number of examined buildings

Analyzed buildings	Al-Balad	Al-Salamah
Total number	2046	6050
Analyzed buildings	308	714
Percentage	15.05%	11.80%



(a) Al-Balad

(b) Al-Salamah

Fig. 1 Areas of investigation, (a) Al-Balad and (b) Al-Salamah districts of Jeddah

Based on previous inventories for score assignment [11], and knowledge about the most-used building construction of the area, a checklist was prepared grouping the building points into three major areas (Table 4):

- identification of the buildings (district, street);
- general data (age and function of the buildings, regularity in plan and elevation, position of the building, changes in function, previous damages, etc.);
- structural data (construction system, quality of materials, workmanship);
- other remarks.

Outlined here are the major steps were conducted during the field survey:

1. Groups of students from engineering college at University of Jeddah were selected to conduct the survey as part of their assessment in statistics course (INE 331).
2. Google maps were used to determine area for each groups from those two districts.
3. The process in conducting the interview with the resident and the survey questions was explained to the students.
4. After submitting, results were checked by experts.

Table 4 Points of the checklist for collection of building data [11]

1. IDENTIFICATION OF THE BUILDING	
1.1. Number of the building	
1.2. Function	
1.3. Pictures of the building should be uploaded	
2. GENERAL DATA	3. STRUCTURAL DATA
2.1. Construction date	3.1. Structural system
2.2. State of the building	3.2. Later conversions
2.3. Relationship to adjacent buildings	3.3. Direction of structural system
2.4. Mass or elevation	3.4. Orientation (of the plane of street elevation)
2.5. Layout	3.5. Type of foundation
2.6. Form of the roof	3.6. Material of vertical structure
2.7. Basement	3.7. Material of horizontal structure, type of the slab
2.8. Number of stories (without basements and attic)	3.8. Material of roof
2.9. Attic is used for living space	3.9. Type of outer coverage

Visual inspection was carried out by trained volunteers during the field survey done through the period between June and August 2016. Data was uploaded on to an online interface with a total number of 1192 filled in questionnaires.

After a validation procedure, the remaining 1022 buildings (11-15% of the buildings in a district) were evaluated and scores were assigned based on FEMA. Assigning the building type, materials, time of construction etc., did not require an extensive knowledge of structural performance. Therefore, a large number of structures could be screened in a short amount of time.

What was more challenging was to make sure the buildings were constructed as they were indeed supposed to be (reinforcement, quality of concrete, walls and beams removed or heavily modified then covered with non-structural materials). This could be part of a second stage of evaluation.

5. TYPICAL BUILDING STRUCTURES

The Saudi Building Code (SBC), like all codes, has evolved over many years as design methods have become more refined and the effects of seismic loads better understood. All codes define procedures to estimate drift and set allowable limits, however difference occur when there may be large discrepancies in the stiffness of a building frame due to soft stories or geometric/structural irregularities due to effective stiffness of structural members as discussed above [12].

Previously, zoning for earthquake areas for Kingdom was made on the basis of UBC-91, Later on with the development of seismic codes throughout the world; seismic maps in the Kingdom were modified based on IBC 2003. According to seismic maps, most of the Kingdom regions are no- and low-risk levels. Areas along the western coast, especially in the northwest and southwest are considered to be of moderate risk level [13].

The present Saudi Building Code uses seismic design categories, building ductility classifications with response reduction factors, soil factors, and load combination factors; much like Eurocode, IBC, and US codes. The new Saudi Building Code was enacted in 2007.

Table 5 Main features of examined buildings

Analyzed buildings	Al-Balad	Al-Salamah
Number of buildings	308	714
General building condition		
Good	54%	**81%**
Minor restoration needed	46%	17%
Construction period		
1965-1975	**32%**	-
1976-1982	**31%**	6%
1983-2007	13%	**64%**
After 2007	1%	30%

Construction period has been determined based on changes within the building codes. Findings about the buildings based on the visual screening were consistent and reasonable considering the age of buildings based on the data obtained previously (Table 5 and Fig. 2).

Typical structures in both districts of Jeddah City are reinforced concrete beam-column frames with fairly rigid diaphragm floors (Fig. 2). The proportion of this type of the building was even higher in recently built area of Al-Salamah District.

Older buildings are more massive in beam/column dimensions with generally less reinforcing. Much of the frame systems are infilled with unreinforced masonry. Often it is difficult to evaluate the timing and extent of the infill work, especially on older buildings. More modern designs may cast the concrete frame directly on infill walls so that there is very tight confinement of the infill. Older buildings are often modified to accept new utilities, changes in floor plans or other modifications and infill walls are partially or fully removed, or new walls put in place.

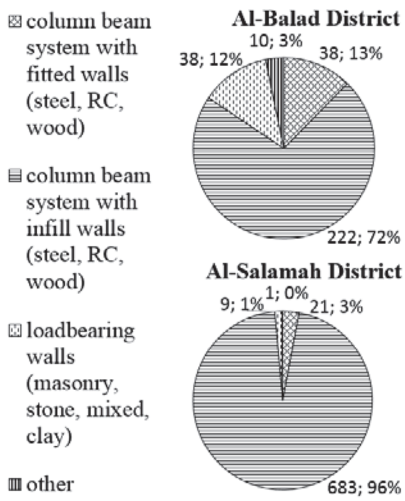


Fig. 2 Typical structural support Al-Balad and Al-Salamah Districts (number and percentage)

Mixed use buildings often have commercial or business space that occupies the ground floor. Such spaces often have more open floor plans to allow for easier access. This leads to problems of soft stories where the lower columns do not have shear walls (or significantly less shear stiffness) than the remaining upper floors. Other issues such as methods of attaching fascia materials and other architectural details are often not known.

6. DATA ANALYSIS OF RVS PROCEDURE

All survey data were entered into an Excel spreadsheet. Due to some of the complexity of decisions, a series of evaluation functions were programmed in Visual Basic for Applications (VBA) which resides within the Excel software. These functions could read a building record, decide the basic hazard score, and then read additional information to determine score modifiers. The only general requirement was that the building records remained consistent in their description of the various features of the building.

A similar set of VBA routines was developed for evaluating hazards in Gyor, Hungary [11] and more detailed information about the routines can be found there. Using the programmed functions also made it easier to detect data entry errors and to examine possible scenarios where soil types or building performance can be modified.

Table 6 Distribution of structural class

Structural class	**Al-Balad**	**Al-Salamah**
W1 (wood-frame)	1	-
S3 (light metal buildings)	1	2
S5 (steel frame with infill walls)	-	5
C1 (concrete moment-resistant frame)	37	19
C2 (concrete shear-walls)	9	6
C3 (concrete frame with infill walls)	176	676
RM1 (reinforced masonry)	46	2
URM (unreinforced masonry)	38	4
Total	308	714

Classification of the buildings was the first step to perform in the analysis (Table 6). The vertical structure of the building and the material of this structure were taken into account. Most structures were classified as concrete moment-resisting frame with infill walls.

Basic structural score was determined for each building based on the visual inspection considering the structural system and the moderate seismicity of the region (Table 7).

Additional modifiers were applied to account for proximity of neighboring buildings, construction practices, building codes applied for design, and plan/profile irregularities:

(i) Vertical irregularity modifier was determined based on mass compactness or irregularity and the relation to adjacent buildings in case of older city part. There are strict rules according to new codes for the distance between the adjacent buildings from 1.8 to 2 meter. However in Al-Balad area the buildings are built closely having separate infill walls with a few cm of dilatation.

(ii) Construction code modifier was used in case of buildings built before 1983 with a pre-code modifier, and a post-code modifier was taken into account for buildings built after 2007 according to new code. Saudi Building Code was enacted in 2007.

(iii) Mid-rise modifier was determined for buildings having more than 4 stories.

(iv) Soil score modifier was evaluated based on interviews with a soil testing company (Al Jazar Consultant Office). According to their finding the typical soil is a mix of coral in the top level of the soil and sabkhas in most of the areas in Al-Salamah District. On other hand, mud soil is usually in Al Balad District.

Table 7 Distribution of typical BSH scores

BSH of buildings	**Al-Balad**	**Al-Salamah**
3,00	37	19
3,20	176	676
3,40	38	4
3,60	55	13
3,80	1	2
5,20	1	0
Total	308	714

For analysis, soil type D was assumed (Table 8) based on information got from soil testing company and publications on soil analysis of the area.

Table 8 Soil analysis findings in Al-Salamah [14]

Depth [m]	Soil type
1	Sand silt with mud and brown stone – medium density
2	
3	Coral crumbly been extracting gravel or sand graded light gray to white is very incoherently to medium density
4	
5	
6	
7	
8	
9	Soft sand to an average roughness with brown silt – medium density
10	

Based on BSH scores and score modifiers a final structural score can be obtained. A final score greater than or equal to 2.0 would indicate that no further seismic evaluation is needed. Scores lower than 2.0 indicate additional evaluation is warranted.

A bar chart of scores for Al-Balad and Al-Salamah are shown in Fig. 3 and 4.

In Al-Balad, most of the 300 structures evaluated fall well below the 2.0 level with some reaching a negative score. The distribution shown in Fig. 3 is typical when there are only a few varieties of buildings examined.

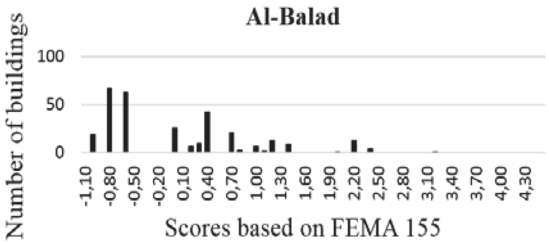


Fig. 3 Scores of buildings in Al-Balad District

This means that there are a limited combination of features and scores to be counted and so there are 4 clusters of scores: the lowest around -0.8, the next 0.4, a third around 1.1 and finally a few buildings at 2.2. Negative scores would indicate unreinforced masonry construction of multiple stories with a "soft" ground floor, irregular plan or profile, and perhaps neighboring buildings directly attached to the building.

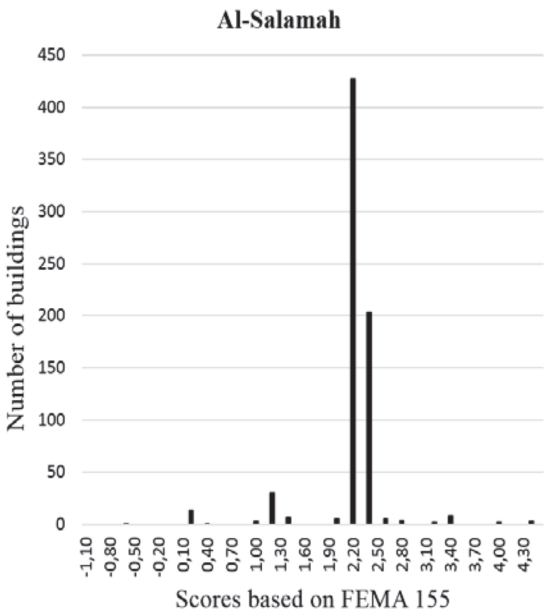


Fig. 4 Scores of buildings in Al-Salamah District

In the newer Al-Salamah District, the buildings are generally reinforced concrete with masonry infill, built according to more recent codes with a higher quality of construction. Most of the buildings pass the 2.0 score threshold. Since more than 700 buildings were examined in this district, the bar chart is somewhat misleading; there are still a significant number of structures below the 2.0 threshold.

7. COMPARING THE SCORING RESULTS

Fig. 5 illustrates the influence of time of construction as well as type of building. The distribution of final structural scores are in line with the assumption of having more vulnerable buildings in an older city district than in a more recent built city part.

In the Al-Balad District, most of the buildings are older while in the Al-Salamah District a much higher percentage are newer construction. The impact is perhaps due to the changes to Saudi Arabian building codes in the 1980's and 90's. The same trend can be found in many cities. (Note that the tops of the two highest bars were shortened to fit the graph more easily.)

8. CONCLUSIONS

Earthquake risk is a public safety issue that requires appropriate risk management measures and means to protect citizens, properties and infrastructures. The aim of a seismic risk analysis is to estimate the consequences of seismic events of an investigated area, on a regional or state level. The evaluation demonstrates the relative ease and low cost of the RVS system. Districts, or even city blocks, can be delineated with respect to how much seismic rehabilitation will be needed. However, since most of the scoring is based on experience in the U.S. and other countries, a more rigorous evaluation of structural performance under seismic loads would be helpful. Calibrating the scoring system to a specific building stock will create more confidence in the evaluation system.

The results of the investigation so far show the influence of age on expected seismic performance, the different level of vulnerability and the areas where intervention is needed. This is due mainly to evolution of building codes, building material quality, and construction methods. Modern designs tend to be more regular in form as well. The presented case study is rather offering the steps that should be performed to determine seismic risk of a city than being a finalized risk assessment for the city of Jeddah. This study offers the method that can be applied for further analysis of the city meanwhile stressing the clear differences of vulnerabilities for residential buildings built based on different seismic codes. Further research will be directed toward other districts in the city as well as performing more rigorous analyses (pushover, dynamic response) on selected typical building types. Additional work on determining the impact of soft, sabkhas soils on the response of short medium and tall buildings is also necessary.

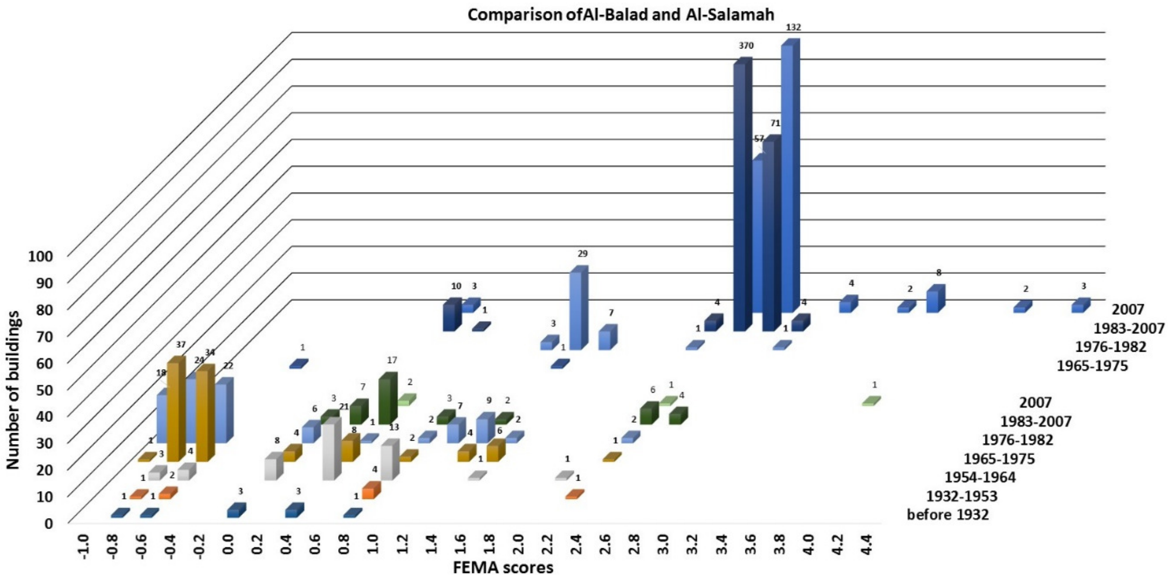


Fig. 5 Final Structural Score distribution of evaluated buildings

9. ACKNOWLEDGEMENTS

This project was funded by the Deanship of Scientific Research (DSR), University of Jeddah, Jeddah, under grant no. G/1436/966/570. The authors, therefore, acknowledge with thanks DSR technical and financial support.

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