On the Nonstructural Elements and Their Behavior in the Bam Earthquake of 26 December 2003

Mahmood Hosseini

Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, email: hosseini@iiees.ac.ir

ABSTRACT: *Regarding the importance of the nonstructural elements in the vulnerability of buildings, and the extensive damages of some of these elements in recent earthquakes, particularly the Bam event, in this paper at first the characteristics of nonstructural elements are briefly reviewed, with emphasis on the Iranian buildings; then the seismic design, vulnerability, and upgrading of these elements are explained and discussed as a state-of-the-art review; and finally, the results of a thorough survey performed on the behavior of and the damages sustained by these elements, particularly the architectural ones, in the city of Bam because of the December26, 2003 earthquake are presented. Finally, based on the results of this survey some recommendations are made which can be useful for modification of the "Guidelines for the Seismic Retrofit of the Existing Buildings", which is used presently in the country as the only official reference in this regard.*

Keywords: Bam; Nonstructural; Seismic safety level; Design provisions; Vulnerability; Upgrading techniques; Seismic retrofit; Risk mitigation

1. Introduction

Nonstructural elements are those elements in a building which are supposed not to participate in carrying the applied loads to the structural system, including the seismic forces. These elements can be divided into four main categories:

1. Architectural elements
2. Mechanical facilities
3. Electrical and communicational facilities
4. Interior equipments

The characteristics of elements in each of the abovementioned categories are not only different from those of other categories, but also are quite numerous and distinct within each category, particularly in the case of architectural elements. This great variety of characteristics has made the study of their seismic behavior much more difficult than the building structural elements. This can be claimed to be one reason behind the fact that the seismic study of these elements has started much later than the studies of structural elements. Another reason is the discarding of structural engineers with regard to the design of nonstructural elements as they are usually believed to be designed by architects or by the designers of mechanical and/or electrical facilities. The main reason has been obviously the fact that the total collapse of or severe damage to the building structures in past earthquakes has diverted the attention of building engineers from the vulnerability of the nonstructural elements. However, these elements have shown their high vulnerability, even in recent earthquakes, in which the level of structural damages has been comparatively low.

Past earthquakes have proven that the nonstructural elements are highly vulnerable, if not designed for earthquake excitations. The consequences of the nonstructural elements vulnerability can be summarized as follows:

- Direct damages
- Premature collapse of the building
- Creating post earthquake fires
- Spreading hazardous materials
- Interrupting the rescue activities

A brief explanation on each of the above mentioned consequences is given here. Since the costs of construction and/or installation of the nonstructural elements versus their relative volume of the whole construction work are usually much more than those of the building structures, the financial loss due to the direct damage to the nonstructural elements can be relatively high, even when there is no structural damage. This is particularly true in the case of industrial buildings in which the building cost itself is very little in comparison with the costs of interior equipments.

The premature collapse of a building by the nonstructural elements may be accelerated by the uncounted for contribution of these elements to carrying of the lateral seismic load. Damage to either mechanical or electrical systems can easily result in fires. Some samples of these fires have been observed in the Bam earthquake as discussed in section 4 of this article.

Spreading the hazardous material is another consequence of damage to mechanical facilities. This is particularly true in industrial buildings, in which various chemicals are used.

Interrupting the rescue activities because of damage to the nonstructural elements is a case which has occurred in some hospitals in the past earthquakes. A similar case occurred in Bam airport, in which damage to the nonstructural elements interrupted the operation of the Control Tower as discussed in section 4.2 of the paper.

As mentioned before, the study of seismic behavior of the nonstructural elements has started much later than the structural elements of buildings. One of the first attempts in this regard was a workshop held by Earthquake Engineering Research Institute (*EERI*) in 1983 with the objective of reviewing and evaluating the status of nonstructural elements [6]. The studies continued since then in various forms from mathematical modeling to retrofitting techniques to their effect on the emergency function of an essential building. For example, Henry and Stein (1987) conducted a comparative study of the effects of cladding panel modeling [14]. They studied the macroscopic effects on the behavior of a two story, one bay frame with a single cladding panel at mid-height when cladding panels are structurally incorporated into the analysis. The results indicate that incorporation of cladding panels results in a dramatic reduction in a structure's natural periods of vibration.

In early 90s the Applied Technology Council (*ATC*) held a seminar and workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures, in which several issues with regard to the nonstructural elements were addressed. As an example, the seismic performance database based on the study of more than 100 major facilities and many smaller facilities and hundreds of buildings located in the strong-motion areas of 42 earthquakes that have occurred in California, Latin America, Europe, Asia, and the Pacific region since 1971 can be mentioned [52]. More examples of the studies reported in that workshop, which were published later as the *ATC*-29, are mentioned in section 3 of this paper.

In a state of-the-art report by Soong [43] the seismic behavior of nonstructural elements the importance of nonstructural issues in seismic design and performance evaluation was emphasized [43]. In a study on the nonstructural damage from the Northridge earthquake by McKevitt, et al [25] potentially hazardous nonstructural damage was pointed out with more emphasis [25]. As a good example of detailed analytical studies on the seismic behavior of the nonstructural elements the study by Pantelides, et al [33] can be mentioned. They worked on the development of a loading history for seismic testing of architectural glass in a shop-front wall system. In their work a systematic analytical study of the effect of the *S*00*E* component of the 1940 *E*l Centro earthquake on the response of a one-storey glass and aluminum shop-front wall system was presented. The seismic response of a one-storey commercial building comprised of three reinforced masonry walls, a glass and aluminum shop-front wall system, and a steel bar joist metal deck roof system was determined using the *ABAQUS* and *SAP* 90 finite element packages [33].

One of the first experimental works on the nonstructural elements was conducted by Negro and Colombo [32]. They made some full-scale pseudodynamic tests on a four-storey framed structure designed according to Eurocode 8, with different infill configurations. Their results showed that an irregular distribution of the panels yields unacceptably large damage in the frame. In addition, it was shown that even a regular distribution of infills can lead to irregular behavior of the frame [32]. Another experimental study was conducted on the seismic horizontal force of nonstructural systems mounted on the buildings using a shaking table [27].

In that study the nonstructural systems mounted on two conditions of main structures, fixed base and isolated structures, were examined using several earthquake motions. The acceleration responses of the nonstructural systems, the amplification factor relative to the input ground accelerations, and the horizontal force coefficients were observed, and comparison between the experimental results and the 1997 *UBC* and the 1997 *BCJ* design codes were also conducted [27].

In the second seminar of *ATC* on the nonstructural elements, held in 1998, Seismic Design, Retrofit, and Performance of nonstructural components were discussed. As a sample of studies presented in that seminar, whose contents were published as the *ATC* 29-1, the work reported by Porter and Scawthorn [34] can be mentioned, in which the seismic reliability of critical equipment systems such as fire protection systems in high-rise buildings was studied [34]. In that study attaining seismic reliability was reported to involve several steps, including: 1) modeling the equipment and the system they constitute with regard to seismic performance, 2) assessing the risk posed by failure of the equipment due to a major earthquake, 3) determining an appropriate criterion, or level of reliability, and 4) cost effectively assuring the reliability.

The seismic response of nonstructural systems mounted on the suspended pendulum isolation (*SPI*) devices was also studied by shaking table test [26]. As compared to the results of the reference fixed structures, it was found that the utilization of the *SPI* system produced the significantly low acceleration amplification factors of supported nonstructural systems. The *SPI* system also gave relatively constant amplification factors along the natural period of nonstructural systems and over the various input ground excitations. Comparison between the experimental results and two nonstructural design stipulations of the 1997 Uniform Building Code and the 1997 Building Center of Japan was also conducted to show that the horizontal force coefficients of nonstructural systems mounted on isolated structures are sufficiently lower than the maximum provided design values [26].

Following the work of Yanev, [52], Kao, et al [16] developed a nonstructural damage database. That database provides information on earthquake-caused damage to nonstructural elements in buildings and other facilities from the 1964 Alaska earthquake to the present. It contains nearly 3,000 entries encompassing more than 50 earthquakes [16].

Recently the nonlinear analysis of nonstructural components was studied by Villaverde [50]. He proposed a design-oriented simplified method for the seismic design of nonlinear nonstructural components attached to nonlinear building structures. His method is based on a previously developed simplified procedure for linear systems that is analogous to the reduction of response spectrum ordinates by a ductility factor and involves the use of reduced natural frequencies and augmented damping ratios to linearize the nonlinear systems [50].

More recently the nonstructural seismic preparedness of Southern California hospitals was taken into consideration [51]. They tried to assess the level of adoption of nonstructural seismic hazard adjustments by hospitals in Southern California, and to identify the factors that led to adoption of these adjustments. Results provide evidence that hospitals in Southern California have partially implemented a variety of earthquake preparedness and mitigation activities. However, many adjustments specific only to earthquake hazard were not commonly implemented, and this is cause for concern [51]. Finally, very recently the effect of damage to nonstructural elements in a hospital evacuation was studied [38]. Based on a study on the 1995 Kobe earthquake they have reported that the immediate nonstructural damage, after even a moderate earthquake, can put a hospital at serious risk [35].

It is seen that the nonstructural elements have been looked at by researchers from many different viewpoints. However, the ongoing research shows that there are still some problems with regard to these elements which need more investigations. Among these, the studies done on the three following subjects are of more importance, since they are more related to the "seismic risk mitigation" as the main goal: 1) the seismic design provisions and recommendations, 2) the seismic vulnerability evaluation, and 3) the seismic upgrading techniques. The works done with regard to these subjects are reviewed in detail in section 3 of this article to help making better decisions on the future works in this field. However, before the review, it is helpful to have a brief explanation of the characteristics of the nonstructural elements, which make them different from the structural elements, particularly in the case of Iranian buildings. These are discussed in section 2 of the paper. After the review in section 3, the behavior of nonstructural elements in the Bam earthquake is studied in section 4, and finally based on the Bam observations some discussions and recommendations are presented in section 5 of the paper, which are useful for revising the corresponding chapter in the "Guidelines for the Seismic Retrofit of the Existing Buildings", which is used presently in the country as the only official reference in this regard.

2. Characteristics of the Nonstructural Elements

In spite of different specifications for various kinds of the nonstructural elements, these elements have some general physical characteristics which make them different from the structural elements from the seismic behavior point of view. Furthermore, in the case of Iranian construction styles, and also because of some cultural fact in Iranian lifestyle these elements have some particular features which can not be found in conventional types of building construction and use in other countries.

2.1. General Characteristics

Most of the nonstructural elements have the following general mechanical specifications which makes them different from the structural elements, such as steel or reinforced concrete members, which are generally utilized for seismic resistant design of buildings:

- High initial stiffness
- Low ultimate strength
- Brittle behavior subjected to dynamic loads

Masonry nonbearing walls and partitions, façades and claddings, mechanical pipings, and some of interior facilities, which are attached to the building such as cupboards and shelves, are all samples of the nonstructural elements having the abovementioned characteristics. The first specification makes the whole building structure stiffer than the building skeleton alone. This means a lower natural period which usually results in higher seismic forces received by the building. Obviously, these high seismic forces will act on all elements showing resistance against the loads, regardless of being structural or nonstructural. The high imposed forces to the nonstructural elements on the one hand, and their second and third specifications, namely the low ultimate strength and brittleness, on the other, will make these elements to get damaged or even fail just in the very first moments of earthquake excitations. It is notable that if the nonstructural elements are not permitted to act as parts of lateral resisting system to participate in carrying the lateral seismic loads, the value of the seismic forces received by the whole building system would be much less, as the stiffness of the building skeleton alone is lower than the combined structural and nonstructural system.

Another adverse effect of the participation of the nonstructural elements in carrying the lateral loads raises from the non-uniform distribution of these elements in the plan of the buildings, which is almost inevitable. This non-uniformity on the one hand, and the high stiffness of these elements, on the other, can causes the building center of stiffness to be much farther of the building center of mass than what has been considered in the design based on the building skeleton alone. This uncounted eccentricity can make the even a building with regular and symmetric structural system behave torsional, and this additional torsion in turn can result if excessive damage or even collapse of the building.

The two abovementioned facts have encouraged many researchers and designers to work on the idea of isolating the nonstructural elements from lateral load bearing system of the building. This isolation idea can be easily applied if the nonstructural elements are lightweight, but if these elements are heavy, which is the case for most of architectural nonstructural elements in Iranian buildings, the isolation idea can not work well. This problem is discussed in the following subsection with more details.

2.2. Particular Features of the Nonstructural Elements in Iranian Buildings

In the case of Iranian buildings there are some particular features which make the nonstructural elements of these buildings different from those of other countries, especially US and Japan as the two developed seismic countries. Some of these differences are due to the different building construction styles in Iran and the US, and some others relate to the lifestyles in the two countries, which is basically a cultural problem. Regardless of their roots, these differences are of great importance as the Iranian codes have been developed and are still being developed mostly based on the *US* corresponding documents. These features are different depending on the category of the nonstructural elements as follow.

2.2.1. Architectural Elements

This group has the most different features from the corresponding group in developed seismic countries, and is the most problematic group among the nonstructural elements in Iran. The particular features of this group are:

- Heavy weight
- Low inherent integrity
- Weak connection to supporting structure

The external walls and internal separating walls and partitions, made of massive brick masonry, as well as the stone facade or cladding, particularly the 3*cm* brick finishing of the external walls, are samples of architectural components having all of the abovementioned characteristics. Internal veneer, such as ceramic tiles, and internal walls and ceiling finishing are samples of components having the second and the third characteristics. The top wall and the parapet cornices are the sample components having the first and the third characteristics. Finally, window frames are the sample components which have the third characteristics in Iranian buildings.

2.2.2. Mechanical and Electrical Elements

This group of the nonstructural elements can be considered as the second problematic group because of the following features:

- Having various manufacturing standards
- Mostly installed without any specific standard

In fact, most of the major mechanical and electrical equipments, such as *HVAC*, are imported from abroad, and in many cases from the northern European countries, which are not earthquake prone, and accordingly do not have any specific seismic provisions. Furthermore, although these countries usually have high installation standards, the installation in Iran is done mostly by non-expert people who do not follow the installation instructions properly, and therefore, even if the equipment is from a seismic prone counties, and has the required anti-seismic installation instructions those measures usually are not actually implemented.

2.2.3. Interior Equipments

This group has also some differences with those in other seismic countries, particularly the *US*. These differences are as follow:

- They either are, or are occupied by fragile objects, particularly in the case of house internal ornaments
- They are mostly heavy and are installed as hanging objects from the ceilings in many parts of the building

These two features have basically cultural roots, for example having several old glass or ceramic jars or other similar objects, and also big and heavy chandeliers in almost all rooms, particularly in more luxury houses is an Iranian tradition.

The special features discussed in this section make the use of design guidelines and also evaluation criteria and retrofitting measures, developed by other countries and discussed in the following section of the paper, inadequate in many cases, and therefore, some more appropriate methods and techniques are required to be developed.

3. Studies on Seismic Design, Evaluation, and Upgrading of the Nonstructural Elements

As mentioned in section 1 of the paper several studies have been performed on the nonstructural elements since late 70*s*. However, among these studies those related to the seismic design, vulnerability evaluation, and retrofitting techniques are more important for the "seismic risk mitigation" purposes. Therefore, in this section of the article a state-of-the-art review on the seismic design, evaluation, and upgrading of the nonstructural elements is presented.

3.1. Seismic Design Provisions and Recommendations

The first seismic design provisions for nonstructural components in buildings can be found in the 1978 *ATC* 03 report. These provisions were discussed to some extent in the *EERI* [6] publication based on the workshop held in April 1983 with the objective of reviewing and evaluating the status of nonstructural elements as considered factors in seismic design and construction, with emphasis on the status of and need to improve implementation of research [6]. In that workshop four issues were discussed, which include life hazards, structural relationships, institutional roles, and economic losses.

Sakamoto, et al [37] proposed some methods for aseismic design of nonstructural elements based on experiments and field surveys [37]. Their work basically was focused on exterior walls and partitions, particularly falling of broken glass, and to some extent on the environmental design. Hirosawa, et al [15] presented a state-of-the-art report on seismic design of building equipment and nonstructural components in Japan [15]. They reported various kinds of damage to the nonstructural elements, including broken windows and water storage tanks, loss of exterior and interior finishing, and battered furniture. They also mentioned that in reinforced concrete buildings, the nonstructural walls have often caused a brittle failure of structural columns, with displaced doorway sashes preventing people from entering or exiting.

In an overview of the building code seismic requirements for nonstructural elements Porush [35] suggested some replacements for some the Uniform Building Code provisions [35]. Also Lai and Soong [19] proposed some seismic design recom-mendations for the secondary structural systems [19]. They showed that by selecting an optimum damping of the support, the maximum acceleration of the secondary system can be minimized and that this damping ratio is relatively insensitive to the earthquake input. On the other hand, the relative displacement between the secondary system and the structure can always be decreased by increasing the support damping. Compromises thus need to be made when there is a conflict in achieving the best global secondary system performance.

Haupt [13] discussed the barriers and challenges in developing seismic code rules for equipment and non-building structures. He has mentioned that developing requires the identification of the disparate groups involved, defining and making concrete the appropriate interface parameters between the definition of seismic effects and acceptance criteria, developing tiered acceptance criteria consistent with defined hazard, and developing long-term relationships among organizations preparing rules. Some simplified procedures for seismic design of nonstructural components were also proposed by National Center for Earthquake Engineering Research (*NCEER*) [40], in which an assessment of the current code provisions of that time was also done. In their assessment the 1978 *ATC* 03 report provisions, adopted with some minor changes by the 1991 *NEHRP* Recommended Provisions that were used as the basis for the first generation seismic force provisions for the design of nonstructural components in codes and manuals of that period were critically evaluated, and improved procedures were proposed for incorporating of the dynamic characteristics of the supporting structure as well as the nonstructural components.

In another *NCEER* report the research accomplish-ments on the code development for nonstructural components have been discussed [42]. Focusing on the 1991 NEHRP (National Earthquake Hazard Reduction Program) provisions, he tried to identify their shortcomings, and to recommend revisions which would bring them more in line with the state-of-the-art knowledge of the time in this area. His revisions were recommended within the framework of the equivalent lateral force format for practical applicability. Villaverde [48, 49] also proposed a replacement for the seismic code provisions for nonstructural components in buildings [48, 49]. He tried to develop a procedure to determine in a rational but simple way the lateral forces for the seismic design of nonstructural components attached to buildings based on the results of studies on seismic response of secondary systems. It takes into account the dynamic interaction between the structure and the nonstructural component, the level above the base of the structure of the point or points where the nonstructural component is attached to the structure, and the number of such attachment points. It uses, in addition, the design spectra specified by building codes for the design of the structure as the earthquake input to the nonstructural component.

Sucuo lu and Vallabhan [46] worked on the behavior of window glass panels during earthquakes [46]. Based on the review of glass damage observed in past earthquakes and previous research on the seismic performance of glass components they evaluated the seismic design code procedures proposed for mitigating the damage sustained by glass components. They developed some analytical procedures for calculating the in-plane deformation capacity and out-of-plane resistance of window glass panels subjected to seismic excitation, and proposed some simple practical procedures for the design of glass panels against earthquake effects. Their procedures account for the inter-storey drift displacements and floor responses of multi-storey buildings as well as the mechanical properties of the window glass.

Freeman and Kehoe [11] performed a review on the *NEHRP*-94 Recommended Provisions, in which two alternate methods for determining the horizontal seismic force for architectural, mechanical, and electrical components is suggested: one method specifies a constant acceleration over the height of the building, and the other assumes a linear distribution of acceleration over the height. Comparing with the 1994 Uniform Building Code (*UBC*-94) seismic design provisions, in which the lateral forces on nonstructural components and equipment are calculated by a formula based on the assumption that the horizontal acceleration of the component is constant over the height of the building, Freeman and Kehoe tried to judge the *NEHRP* recommended provisions by the recorded data from the instrumented buildings subjected to earthquakes [11]. Freeman [10] also tried to summarize the provisions of the Tri-Services guidelines to be used as a basis for performance-based engineering of nonstructural components [10]. (The

1982 edition of "Seismic Design for Buildings" manual by the Departments of the Army, Navy, and the Air Force is generally referred to as the Tri-Services manual, and it its supplements, "Seismic Design Guidelines for Essential Buildings" (1986) and "Seismic Design Analysis for Buildings" (1996), dynamic analysis procedures for nonstructural components are presented that account for both elastic and inelastic response of the building to earthquake ground motion. Those design manuals provide criteria for two levels of earthquake motion, methods for approximating floor response spectra, performance requirements of nonstructural components, and design examples.)

Gurbuz, Wu, and Wittchen [12] reviewed the evolution of the requirements for design of nonstructural components and their anchorage, including *UBC*-94, *UBC*-97, and the draft International Building Code (to be *IBC*-2000 later) and showed that classical design and anchorage practice for some heavy equipment may not meet the *UBC*-97 or *IBC*-2000 provisions [12]. A similar study on the development, evolution, and application of the earthquake design force for nonstructural elements was also done by Bachman, and Drake [3] based on the *UBC* and the *NEHRP* provisions. Bachman [2] also presented a comparison of design forces for typical applications for the *UBC*-94, *UBC*-97, and *IBC*-2000, and mentioned that one primary difference is that the *UBC*-94 forces are to be used with working stress design and the *UBC*-97 and *IBC*-2000 forces are to be used with strength design. Therefore the *UBC*-97 and *IBC*-2000 design forces are typically 1.4 times greater than those found in the *UBC*-94.

Kehoe and Freeman [17] also criticized the procedures for calculating seismic design forces for nonstructural elements by comparing *UBC*-94 and *UBC*-97. They studied the effects of the significant changes in *UBC*-97, including the introduction of an *R* factor for nonstructural elements, the use of soil factors in determining the design force, and the variation of the design force over the height of the building, by comparison of design forces between the *UBC*-94 and the *UBC*-97 for rigid and flexible elements, and by comparison with dynamic analysis and building response data. They claimed that the comparisons results do not provide justification for the radical changes in the *UBC*-97. On this basis they proposed restoring the provisions of the *UBC*-94 with some minor modifications, including inclusion of an amplification factor on the design acceleration for roof-mounted elements and improved procedures for calculations of amplification of flexible or flexibly mounted equipment based on the procedures developed in the Tri-Services manual. They also made some recommendations for further research to improve the design procedures.

An interesting case of seismic design of intricate exterior cladding systems was reported by Krakower, et al [18]. In their report it is mentioned that successful seismic design of intricate exterior cladding systems requires awareness of many factors. When some or all of the factors are not considered, the design and construction of the cladding may affect the construction schedule and may result in incompatibility between the cladding and structural systems that lead to unsatisfactory seismic performance. Working on the reconstructed historic House of Hospitality in San Diego's Balboa Park, which has a complex decorative cladding system of about 3000 highly ornamental pieces of glass fiber reinforced concrete (*GFRC*) cast from molds of the salvaged original staff plaster ornamentation, they mentioned that a refinement of the cladding support occurred after the start of construction to improve the constructability and compatibility of the design. Based on their report the seismic design of the *GFRC* cladding structural system faced conflicting parameters, some of which forced the design and construction team to develop a few typical framing and anchorage details that could be used in a variety of potential support conditions. Once these details were established, the testing program was defined and anchor capacities were obtained. They also mentioned that all of the building systems in the vicinity of the cladding had to be accounted for in order to develop the strategy to simplify the structural system [18].

Another interesting issue with regard to the design of the nonstructural elements is the design responsibility as discussed by McGavin and Gates [22]. Referring to California hospital design their recommendation is a systems approach rather than a component by component approach as is currently the case. They also gave some suggestions how the responsible professionals might be brought into the building design industry [22]. A very interesting case, which was related to the 1994 Northridge earthquake, was reported by McGavin, et al [23]. Based on their report following the 1994 Northridge earthquake the City of Los Angeles established working groups in numerous areas to study the need for possible changes to building ordinances within the jurisdiction of the city. One of the groups was dedicated to studying nonstructural issues, including suspended ceilings. Numerous interests were represented in the nonstructural studies, including the City of Los Angeles, the Division of State Architect, engineers, architects, property owners, academic researchers, and industry representatives. The findings of the suspended ceiling subcommittee were presented to the city for proposed amendments to Chapter 16 (Article 1, Sections 1638 through 1641) of the Los Angeles Municipal Code [23].

McGavin and Patrucco [24] proposed nonstructural functional design considerations for healthcare facilities. Subsequent to the 1971 San Fernando earthquake, California passed its first Hospital Seismic Safety Act mandating that hospitals remain functional. Testimony to the California Seismic Safety Commission following the 1994 Northridge earthquake led to the passage of a second version of the Hospital Seismic Safety Act of 1994 (*SB*1953 Alquist). *SB*1953 is a model code for all jurisdictions in earthquake prone areas where hospital function is a concern. Mentioning the lack of a universally accepted language, code, or definition of what constitutes function or operation McGavin and Patrucco claimed that the majority of owner supplied equipment in the hospital, some of which is life support equipment, receives little or no consideration for seismic qualification. Based on this belief they addressed definitions of function and methods of qualification to better attain a reasonable level of confidence for function for building nonstructural systems and critical owner supplied equipment. They also proposed a "seismic lifeboat" concept that for saving health care providers significant capital outlay over more difficult and questionable methods of attaining function required by *SB*1953. They claimed that their seismic lifeboat concept for health care facilities would make it possible for acute care hospitals to be able to provide basic life saving procedures as well as basic first aid to in-house patients and walk-in injured after a damaging earthquake with a high degree of confidence.

Staehlin [45] also worked on seismic design and performance of nonstructural components in hospitals by discussing the design requirements by the State of California, Office of Statewide Health Planning and Development (*ISOHD*) along with the observed performance of these components during the Northridge earthquake, January 17, 1994. Singh, et al [41] tried to present simplified methods for calculating seismic forces for nonstructural components. Their details of calculating the seismic acceleration coefficients are different, stemming from a study of the response of several buildings analyzed for an ensemble of recorded ground motions. They compared forces calculated by their proposed approach with those calculated according to the *NEHRP*-97 and the UBC-97 provisions, and also with the forces that could have been caused in the nonstructural components by the 1994 Northridge earthquake. Their provisions proposed to reduce the force required for rigid components and to increase forces on the flexible or flexibly mounted components. Finally, Drake and Bragagnolo [4] also described the development, evolution, and application of the earthquake design force provisions of the *UBC*-97 and the *NEHRP*-97 for elements of structures and nonstructural components. Their claim is that engineers and architects need to become informed regarding a variety of earthquake design force provisions.

3.2. Seismic Evaluation Methods

The first studies on seismic evaluation of the nonstructural elements started just a few years after the first works on their seismic design. Reitherman [36] did a study on reducing the risks of nonstructural earthquake damage, and presented a practical guide which was published by the *U.S.* Federal Emergency Management Agency (*FEMA*) as *FEMA* 74. This *FEMA* series booklet provides practical information to owners, operators, and occupants of office and commercial buildings on the vulnerabilities posed by earthquake damage to nonstructural items and the means for mitigating these problems. The booklet has two specific objectives: 1) to aid the user in determining which nonstructural items are most vulnerable to earthquakes and are of most concern, and 2) to point the way toward implementing cost-effective countermeasures.

Drake and Richter [5] performed a study for earthquake hazard mitigation of nonstructural elements in *U.S.* postal service facilities [5]. That paper presented a description of work in progress to identify potentially hazardous nonstructural elements in the *U.S.* Postal Service (*USPS*) facilities and to provide recommendations for upgrade of elements and supports for the life safety level. That work was supposed to be incorporated into the Applied Technology Council's *ATC* 26, a handbook for practicing structural/ earthquake engineers and *USPS* staff engineers to evaluate existing *USPS* facilities.

Arnold (1998) worked on the requirements for nonstructural components for the *NEHRP* guidelines for the seismic rehabilitation of buildings [1]. He acted as the team leader for the development of the requirements for Architectural, Mechanical and Electrical Components for the *NEHRP* Guidelines for the Seismic Rehabilitation of Buildings (*FEMA* 273). In that paper the methods by which a range of performance levels and objectives was accommodated is discussed. Other issues outlined are the scope of the nonstructural components to be considered, the categorization of nonstructural components as acceleration-sensitive or deformation-sensitive, issues relating to means of egress, the nonstructural damage states, and the definition of the operational and collapse prevention levels of performance. Some comments about the difficulties of developing a performance-based set of provisions for nonstructural components are also provided.

3.3. Seismic Upgrading Techniques

The work on seismic upgrading of the nonstructural elements started almost a decade later than the first works on their seismic design. Lagorio [20] published a book entitled “Earthquakes -- an architect’s guide to nonstructural seismic hazards for members of the architectural profession. The book covers some of the latest developments in earthquake hazards reduction prior to the time of its publication. It is divided into the following sections: 1) Earthquake Causes and Effects, 2) General Aspects of Building Performance, 3) Site Investigation, 4) Site Planning, 5) Building Design, 6) Nonstructural Building Elements, 7) Existing Buildings, 8) Urban Planning and Design, 9) Recovery and Reconstruction, 10) Earthquake Hazards Mitigation Process, 11) Recommendations and Summary, and 12) 1989 Loma Prieta Earthquake in the Santa Cruz Mountains of the San Francisco Bay Area Region. An index is also included.

Merz and Cumming [29] presented some recommendations for installation of suspended acoustical ceiling in moderate- and low-risk seismic areas. Following the installation guidance for seismic restraint of suspended ceilings in *UBC* Standard 47-18, which has its origins in a 1972 Ceilings and Interior Systems Construction Association (*CISCA*) Recommended Standard for Seismic Restraint of Direct-Hung Suspended Ceiling Assemblies, and its development for the splay wire restraint requirements in *UBC* 47-18 and their modification during the intervening years for the lateral force design levels specified for Seismic Zone 4 (California), Merz and Cumming discussed the background of the those ceiling restraint provisions and provided separate recommendations for ceiling installation in Seismic Zones 0-2.

Masek and Reitherman [28] performed a study on problems in the implementation of nonstructural earthquake hazard reduction efforts. In that study the authors express their general agreement with the frequently made statement that reducing nonstructural vulnerabilities is cost effective and necessary to reduce significant risks. However, they claim that their experience over the past decade indicates that the barriers to actual implementation are often overlooked. So, the purpose of that paper is to present a summary of solutions to problems that can inhibit implementation of earthquake damage mitigation programs for equipment. Their observations are based upon studies conducted involving in excess of 30 million square feet of processing, manufacturing, computer equipment, mechanical/electrical equipment, and office space. Projects have included design of equipment for new facilities, design of retrofit seismic restraints, and third-party review of restraint designs by others. At the end of that paper some suggestions are drawn from the experience of the authors in working with contractors, facility and risk managers, equipment vendors, and maintenance personnel.

Selvaduray [39] worked on nonstructural hazard mitigation for schools, which was published as *NCEER*-93-0015 report. That report tries to define “nonstructural” and provide the motivation for nonstructural hazard mitigation. It is also tried that typical examples of nonstructural damage during earthquakes are described, with a special emphasis on damaged incurred by schools. Also hazard reduction techniques that are applicable to schools are described, with specific recommendations on what can be done in the office and classroom environment, how the potential of hazardous materials incidents occurring can be reduced, and how mechanical equipment can be anchored.

Fierro, et al [9] presented a practical guide for reducing the risks of nonstructural earthquake damage, which was published as the third edition of *FEMA* 74. That guide was developed to fulfill several different objectives and address a wide audience with varying needs. The primary intent was to explain the sources of nonstructural earthquake damage in simple terms and to provide information on effective methods of reducing the potential risks. However, the recommendations contained in that guide are intended to reduce the potential hazards but cannot completely eliminate them. A few years later Fierro and Perry [8] made a further discussion on FEMA 74. Mentioning that *FEMA* 74, Reducing the Risks of Nonstructural Earthquake Damage -- A Practical Guide, was written to help both the layperson and the engineer to understand, evaluate, and mitigate the risks associated with nonstructural earthquake damage, that paper presents a history of the development of the original document and subsequent revisions, including the third edition by Wiss, Janney, Elstner Assocs., Inc., published in September 1994. Mentioning that the document includes 39 upgrade details that are all categorized as either "Do-It-Yourself" or "Engineering Required" and that the document also includes a Nonstructural Inventory Form, a Checklist of Nonstructural Earthquake Hazards, and a table of Nonstructural Risk Ratings; their paper provides some suggestions for their use in surveying nonstructural earthquake hazards. The authors tried to cover a sample facility inventory using the methodology of *FEMA* 74, and include a summary of suggested improvements and modifications in light of recent developments.

Eidinger and Goettel [7] performed a study on the benefits and costs of seismic retrofits of nonstructural components for hospitals, essential facilities and schools. The cost effectiveness of seismic upgrades of nonstructural components at hospitals, emergency operation centers, city halls, and schools were examined in that paper. They provide examples for bracing of fire sprinkler pipes, upgrades of suspended ceilings, installation of flexible utility connections between buildings, anchoring of equipment, steam pipe upgrades and window retrofits. Also Lama [21] presented some practical guidelines for seismic retrofitting of *HVAC* systems. In that paper Lama deals with the methods developed that allow the contractor to retrofit on *HVAC* equipment, piping and ductwork a seismic system that is practical, economically feasible, proven, and trouble free. He also mentions in his paper that proper snubbing and cable sway brace systems for floor mount and suspended systems, which have no moving parts, are designed not to interfere with the acoustical and vibration systems that are mandated by the Mechanical Engineers and Acoustical Consultants for the *HVAC* systems. These systems also should meet the requirements of the structural engineering community for the foreseeable future.

Meyer, et al [30] worked on retrofit seismic mitigation of mainframe computers and associated equipment as a case study. Their work is a case history of a completed seismic restraint program at a raised floor data center. Their restraint system employs splayed tension cables from the equipment to the concrete floor slab, and anchored equipment includes mainframe computers and related equipment. That paper outlines the three major steps in an actual nonstructural mitigation project including analysis, design, and installation. The analyses included time history dynamic analysis to study the effects of various design parameters on the acceleration of the anchored equipment, and the loads on the anchoring system. The design included consideration of anchor bolts, cable stretch implications, and pre-tensioning. The installation issues included constraints due to obstacles, difficulties in attaching to the equipment, working in a fully operational facility, and cost controls. They also discussed the quality control through testing, submittals, and inspection.

Thiel, et al [47] worked on the seismic retrofit of nonstructural components in acute care hospitals. In that work they mention that the Office of Statewide Hospital Planning and Development (*OSHPD*) has developed technical provisions for the seismic retrofit of acute care hospitals, and that under *SB* 1953 acute care hospitals must be either certified as, or retrofitted to be, life-safe by 2008 and must be capable of maintaining operations following an earthquake by 2030. They also mention that the provisions for nonstructural systems and components are an integral part of the requirements adopted by the Building Standards Commission to meet these performance objectives. These requirements have two distinct aspects: 1) the delineation of the specific systems included in the various performance levels, ranging from the lowest, Nonstructural Performance Category *NPC*-1, to the highest, *NPC*-5, and 2) the technical standards used to achieve the performance. The *OSHPD* modified Division *III-R* -- Earthquake Evaluation and Design for Retrofit of Existing State-Owned Buildings and Existing Hospital Buildings -- of Part 2, Chapter 16, Title 24 is to serve as the standard to be consistent with those standards to be used for other state buildings. That paper presents the technical details of the standard and discusses its application, particularly to typical equipment.

Recently the near-fault issue was taken into consideration. Soong, et al [44] studied the near-fault seismic vulnerability of nonstructural components and retrofit strategies. In their paper they mention that the seismic design of buildings has been well developed and is being continually updated and improved, yet, nonstructural components housed in buildings are rarely designed with the same care or under the same degree of scrutiny as buildings. As a result, buildings that remain structurally sound after a strong earthquake often are rendered unserviceable due to damage to their nonstructural components, such as piping systems, communication equipment and so forth. They also mention that the September 21, 1999, Chi-Chi, Taiwan, earthquake further demonstrates the importance of controlling damage to nonstructural components in order to ensure their functionality during and after a major earthquake. In that paper they assessed damage to some critical facilities during the Chi-Chi earthquake, and addressed two important issues associated with seismic performance of nonstructural components: seismic vulnerability and rehabilitation strategies.

Based on the review presented in this section of the paper it is seen that although several studies has been performed since early 80s on various issues related to the nonstructural elements in the field of earthquake engineering, the occurrence of every new earthquake has created some new ideas which has changed or modified the previously published regulations, guidelines and recommendations. The Bam earthquake is not an exception in this way, and the study and investigation on the behavior of the nonstructural elements in this earthquake can be very useful for the possible required modifications which should be applied to the existing seismic design guidelines, evaluation procedures, and retrofitting techniques to make them more appropriate for the country use. This investigation is presented in the next section.

4. Behavior of the Nonstructural Elements in the Bam Earthquake

The December 26, 2003 earthquake of Bam with magnitude of 6.5, which hit the city of Bam, town of Baravat, and several surrounding villages in Kerman province, destroyed more than 70% of the buildings in the stricken area, and also caused extensive nonstructural damages to the buildings which were remained structurally intact. The observed cases of nonstructural damages are mainly architectural. There are also some cases related to the internal equipments, and just a few cases of electrical or mechanical components. In this section of the paper the damages to nonstructural elements are reviewed based on their categories.

4.1. Architectural Components

The major damages to the architectural components were observed in masonry walls and partitions, internal and external façade and veneers, and particularly stairs. Some damages to false ceilings, glass finishing and windows and doors glasses, parapets and other attachments were also observed as follow.

4.1.1. Exterior Walls Masonry

Several cases of damage to external wall masonry were observed, of which some samples are shown in Figures (1) to (4). It is seen in Figure (1), which is related to the recently constructed Emdad Khodro building located beside the Kerman-Zahedan road, that the external walls in the second story and a part of it in the first story of the building have fallen out. This building had a serious case of pounding as it is shown in the next pictures. The broken glasses of the window in the first story are also visible in the picture. Note that there is no sign of the interlocking between the remained wall in the second floor with the one formerly perpendicular to that, which is now fallen

Figure 1. Collapse of the external walls made of brick masonry in Emdad Khodro building (Photo by M. Hosseini).

out. Also note that in the middle bay at the second story the internal shelf has fallen inward the building. It is also notable that the roof parapet of the building did not get damage, which can be basically because of its short height.

Another case of damage to the external walls is shown in Figure (2), which is related to Khormaye Shargh (East Date) export company. The complete collapse of the end wall of the refrigerating hall is seen in the figure. It is also seen that one wall of the motor house beside the hall has collapsed. A close up of this fallen wall is shown in Figure (3). Examination of the building showed that there was not any internal stabilizing column or external buttress in that end wall. In the case of the motor house wall just its inherent weakness and little integrity with other walls can be the main cause of collapse.

Other samples of the external walls failure are shown in Figures (4) and (5). The little integrity of these walls and their weak connections with the structures are believed to be the main causes of failure in these cases.

Figure 2. Complete collapse of the external wall of the refrigeration saloon of Khormaye Shargh (east date) export company made of concrete block masonry (Photo by M. Hosseini).

Figure 3. Complete failure of the external wall with partial collapse of the ceiling in the motor house of Khormaye Shargh export company (Photo by M. Hosseini).

Figure 4. Collapse of external walls in an under construction R/C building, whose skeleton remained i ntact after the quake - Note to the fallen out window as well (Photo by M. Hosseini).

Figure 5. Collapse of the external wall masonry in the second and third stories of a 3 story steel structure building - the roof parapet has fallen as well (Photo by M. Hosseini).

4.1.2. Yard Walls

Several cases of failure of yard or surrounding walls were observed. Two samples, one brick wall and one hollow concrete block masonry are shown respectively in Figures (6) and (7).

The main reason behind the collapse of these yard walls, as it can be seen in Figures 6 and 7, is in addition to their inherent weakness, the lack of, or the long distance between buttresses [loghaaz-haa].

Figure 6. Toppled brick wall - Note to the fallen parapets as well (Photo by M. Hosseini).

Figure 7. Toppled concrete block (partially brick) wall (Photo by M. Hosseini).

Figure 8. Severely damaged interior wall made of gypsum panels (Photo by M. Hosseini).

Figure 9. Severely damaged interior partition (Photo by M. Hosseini).

4.1.3. Interior Walls and Partitions

Many cases of failure or severe damage to the interior walls and partitions were observed. Two samples are shown in Figures (8) and (9). It can be seen in Figure (8) that although the wall material is gypsum, which is a relatively light material, and although the prefabricated panels are usually of higher quality in comparison with the in situ construction, the lack of integrity and weak connection to the ceiling have caused the failure of the wall. In the case shown in Figure (9) it seems that the very little thickness of the partition has been the main cause of the failure.

4.1.4. Facades

The most popular facade in Bam, as in many other cities in Iran, has been the fine brick masonry cover, called usually the 3*cm* brick facade. The stone tiles are the second some popular materials used as the facade in Bam. Several cases of damage to the 3*cm* brick facades and other brick facades were observed, of which a few samples are shown in Figures (10) to (16). Stone facades have also got damaged in many cases, a sample of which is shown in Figure (17). As it is seen in Figures (10) to (16) no specific pattern can be found for the damage of brick facades. They have got damaged in different building elevations with various forms and areas.

It is noticeable in Figures (11) and (12) that the window glasses have remained intact while the brick facades have gotten severely damaged. It is also notable that the parapet of the logistic building of (formerly) Azadi Hotel (presently Iran Parsian Hotel) has not fallen, which can be because of its little height. It should be noted as well that the Iran Parsian Hotel is located far from the causative fault of the earthquake comparing with the Hijab intermediate school or the city electric substation. However, this building suffered extensive nonstructural damages.

Figure 10. Damage to the so called 3cm brick facade in the second story of the Hijab girls' mid school (Photo by M. Hosseini)

Figure 11. Damage to the so called 3-cm brick facade in the first story of the office building of the city electric substation (Photo by M. Hosseini).

Figure 12. Damage to the brick facade in the top part of the walls in the logistic building of Azadi Hotel (Photo by M. Hosseini).

An interesting point, which is visible in Figure (13), is the lack of cohesion between the main wall masonry and the brick façade. The very clean surface of the concrete block masonry of the wall in this figure shows clearly this lack of cohesion. In the special case shown in this figure it seems the vertical box profiles of the top fence have prevented the façade form the complete collapse. Other interesting point is the detachment of the group of bricks with the used mortar behind them, which are stuck together and made a big piece of debris. It is obvious that falling of such a big piece from a high elevation can be very harmful to the subjected people. Nevertheless, this type of integrity between the bricks and the mortar can help their retrofit as described in section 5 of this paper.

Figure 13. Damage to the brick facade in a yard wall (Photo by Mahmood Hosseini).

Another interesting point can be seen in Figure (14), which shows the fallen brick façade of a residential building. It is seen that in spite of the failure of the façade and the pop out of the windows, the upper part of the façade, which covers the parapet wall had remained almost intact. This can be related to the good cohesion of the brick with the used mortar and also of the mortar with the concrete horizontal tie behind it. (The concrete tie has helped the building to survive the quake.)

Contrary to the cases shown in Figures (10), (12), and (14), the case depicted in Figure (15) shows the failure of the brick facade in the lower part of the building. A reason behind this scattered location of the damaged façade in building elevation can be the non-uniformity of construction work, particularly the used mortars. Figure (15) also shows the failure of the staircase roof (penthouse) which was a very common case observed in the Bam buildings as is discussed in more detailed in the following section of the paper.

Figure (16) depicts a unique case of facade or finishing of a yard wall. It is seen that the masonry of the wall has two separate parts, an inner layer and an outer layer. The inner layer is itself a 3*cm* brick facade, a part of which shown in Figure (13), and the outer layer seems to be a combination of brick masonry and hollow concrete block masonry, finally plastered with a layer of cement mortar. The bricks on the wall, which their larger faces are exposed in the picture, seem to be a filler layer between the two main layers of the wall!

The sample of damaged stone façade is shown in Figure (17). The scattered locations of the detached tiles of the façade on the elevation of the building

Figure 14. Failure of the brick facade in the external wall of a residential building - note to the popped out windows as well (Photo by M. Hosseini).

Figure 15. Damage to the brick facade in lower part of the two story residential buildings - Note to the collapsed penthouse as well (Photo by M. Hosseini).

Figure 16. Damage to the plastered brick and block facade in a yard wall (Photo by M. Hosseini).

Figure 17. Damage to the stone tiles facade in Ban k Mellat building (Photo by M. Hosseini).

indicate again the non-uniformity of the construction work. The interesting point is the detachment of the group of tiles with the used mortar behind them, which are stuck together and make a big piece of debris. This case of stone tile failure was also observed in brick façade as shown in Figure (13).

4.1.5. Stairs and Staircases

Stairs and staircases are among the most vulnerable nonstructural elements, and therefore, are among the most harmful elements in the aftermath of an earthquake as well. Several cases of damage to stairs and the roof structure of the staircases (penthouses) were observed in the Bam earthquake. Some of these cases are shown in Figures (18) to (21) in addition to Figure (15) discussed in the previous section.

It is seen in Figure (18) that the skeleton of the stair case roof has lost its integrity. The same problem is visible in Figures (19) and (20). In a very recent study entitled “Post-Earthquake Quick Inspection of Damaged Buildings in Bam” (Moghadam and Eskandari, 2004) it is reported that in almost 75% of the inspected buildings the main reason of collapse of the penthouses has been the lack of structural system or lack of structural integrity [31]. They also states that according to the inspection in more than 25% of cases both stairs and their sidewalls have been damaged, in more than 20% of cases just the sidewalls were damaged, while the stair itself was undamaged, and in less than 10% of cases, the stair has been damaged, while its sidewall was undamaged.

Figure 18. Severely damaged staircase roof in the office building of the city electric substation-Note to the broken glasses as well (Photo by M. Hosseini).

Figure 19. Damage to the staircase roof in the three story building of Azadi Hotel (Photo by M. Hosseini).

Figure 20. Severely damaged staircase in a commercial building (Photo by M. Hosseini).

Figure 21. Severely damaged or totally collapse penthouses in the residential complex two story buildings (Photo by M. Hosseini).

4.1.6. False Ceilings

The most important building in which this kind of nonstructural damage was observed was the Bam Airport Terminal. It can be realized in Figures (22) and (23) that although the false ceiling parts seem not to be heavy, because of their high length, on the one hand, and the strong vertical component of the ground motion, on the other, they have suffered from a kind of buckling instability, resulted in their falling down.

Figure 22. The deformed parts of the false ceiling in the Bam Terminal Building (Photo by Mahmood Hosseini).

Figure 23. The false ceiling of the Bam Terminal Building, of which some part have fallen down because of instability (Photo by M. Hosseini)

Figure 25. Severely damaged gypsum layer finishing of the interior wall of the Bank Refah Karekaran building (Photo by M. Hosseini).

4.1.7. Interior Veneers

As it is expected there are several types of interior veneers use in the Bam buildings, and almost all types have suffered severe damages. Some samples of damages are shown in Figures (24) to (30). Figures (24) and (25) relate to the Bank Refah Karegaran (The Workers Welfare Bank) building in which several kind of damage to the nonstructural elements were observed including the damages to the interior veneers such as the finishing gypsum layers on walls and ceiling and stone tiles finishing on walls. A reason behind the failure of gypsum layer finishing is the potentially weak line of the electric wire protection tubes as is discussed in section 4-2 of the paper.

The scattered locations of these damages again show the lack of uniformity in the construction process, which was also observed in the facades as discussed before. It is noticeable that in spite of

Figure 26. Severely damaged gypsum layer finishing of the ceiling of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 24. Severely damaged gypsum layer finishing of the interior wall of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 27. Severely damaged stone tile finishing of the interior wall of the Bank Refah Karekaran building (Photo by M. Hosseini).

Figure 28. A big part of gypsum veneer of the ceiling has separated and fallen (Photo by M. Hosseini).

Figure 30. A sample damages to the ceramic tile interior veneers in the bath rooms of Azadi (Iran Parsian) hotel (Photo by M. Hosseini).

having a mezzanine part in this building as shown in Figure (24), which makes building an irregular one, its structural behavior has been almost satisfactorily. It is also notable in Figures (24) and (26) that the sizes of the fallen parts of veneers are quite large and it is obvious that the debris with this size can be seriously harmful to the people, considering particularly the height of the ceiling. This size problem is also observable in Figure (28), which shows a part of ceiling of which a big part of gypsum veneer has separated and fallen.

Figures (29) and (30) show the damages to the interior veneers in the Azadi (Iran Parsian) hotel. The veneers of the upper part of almost all of columns in the lobby were damaged as shown in Figure (29). There were also some damages to the ceramic tile veneers in the bathrooms of the hotel as shown in Figure (30). An interesting point is that just a small part of the column veneer as shown in Figure (29) was damaged, while the lower part which is covered by glass mirror has remained intact. It is not easy to give a reason for this case. This reasoning difficulty is also true for the form of damage in the tile veneer shown in Figure (30).

4.1.8. Glass Facades and Windows

Several cases of damages to the glass facades, thick glass doors, or window glasses were observed, of which a few samples are shown in Figures (31) to (37). The scattered locations of the broken glasses in Figure (31) show again the non-uniformity of the material and construction process. In Figure (32) in addition to the broken glasses of windows the cracked and partially fallen parapet of the Emergency Section of the city hospital is also noticeable. In Figure (33) the size of the broken parts of the thick glass door of Bank Refah Karegaran (The Workers Welfare Bank) can be realized by comparison with the size of the pen cap in the middle of the picture in light blue color.

Figure 29. A sample of damages to the veneers of the columns tops in Azadi (Iran Parsian) hotel (Photo by M. Hosseini)

Figure 31. Damage to th eglass facade of trade and tourism building (Photo by M. Hosseini).

Figure 32. Damage to the glasses of widows in the Emergency Section of the city hospital (Photo by M. Hosseini).

Figure 33. Splashed Parts of the broken thick glass door of Bank Refah Karekaran building (Photo by M. Hosseini).

Figure (34) shows the broken window glasses of a building, while no crack can be seen on the veneer of the walls. The same case is seen in Figures (35) and (36). This shows that the window glass is more vulnerable than the brittle facades. Nevertheless, in

Figure 34. Damage to the glasses of widows in the second story of a residential building (Photo by M. Hosseini).

Figure 35. Damage to the glasses of widows in Bank Saderat Iran building (Iran Import Bank) (Photo by M. Hosseini).

Figure 36. Damage to the glasses of widows in the second story of a residential building - Note to that horizontal damage line in the façade at the level of roof (Photo by M. Hosseini).

Figure (36) a horizontal crack at the level of roof can be seen in the façade which has created because of the movement of the parapet. In fact, this has been that commence of the parapet failure, but because of the short height and relatively high thickness of the parapet it has survived the quake. A similar condition can be seen in Figure (37) in the building located at right, while in the one at left in addition to the breakage of all window glasses the parapet has collapsed as well.

4.1.9. Parapets and Other Attachments

Some samples of damaged or collapsed parapets were discussed in the previous part of the paper. In this part some more cases of damage to parapets and attached tablets and bill boards are discussed as shown in Figures (38) to (41). It is seen in Figure (38) that all parapets in the front elevation of the building have collapsed, while in the other direction the relatively high and slender parapet has survived. This shows the high directivity effect of the earthquake.

Figure 37. Damage to the glasses of widows in the second story of a residential building (Photo by M. Hosseini).

Figure 38. Collapse of parapets in the Iran Insurance Company building (Photo by M. Hosseini).

Figure 39. Partial collapse of parapets in a two story building (Photo by M. Hosseini).

The directivity effect is also visible in Figure (39) in which again just parapets in some specific directions have collapsed, while in other direction they have survived. Figure (40) shows another case of complete collapse of parapets in a two story residential building. Note that in this building the window glasses have remained almost intact. This is because of higher resistance of glasses to out of plane forces in comparison with the parapets, on the one hand, and the directivity effect of the quake, on the other.

Figure (41) shows the collapsed tablets and bill board of a commercial building. Regarding the relatively low weight of the bill boards it can be claimed that the connection between the boards and their frames have not been strong enough to resist the earthquake shock. A part of the stone façade of the parapet has also failed, which is basically because of the failure of the whole parapet from that point to right (not completely shown in the picture). This again confirms the directivity effect of the earthquake.

Figure 40. Complete collapse of parapets in a two story building (Photo by M. Hosseini).

Figure 41. Collapse of tablets and bill boards in a commercial building (Photo by M. Hosseini).

4.1.10. Windows and Door Frames

An almost newly observed phenomenon in this earthquake was the popping out of the windows and some door frames. Some samples of these cases are shown in Figures (42) to (44). This phenomenon can be due to the lack of enough connection between the windows and doors frames and their surrounding walls. In some cases, like the one shown in Figure (44), the popped out window has caused the failure of a part of the wall above it. The absence of the spandrel beam can be also another reason behind the poping out phenomenon and the consequent partial failure of the surrounding walls.

Figure 42. The windows in Iran Khodro building popped out of walls (Photo by Mahmood Hosseini).

Figure 43. A popped ou t window in the electric substation office building (Photo by M. Hosseini).

Figure 44. A popped out window in a one story residential building (Photo by M. Hosseini).

4.2. Mechanical and Electrical Facilities

The cases of damage to mechanical and electrical facilities of building were not observed so much in this earthquake. Nevertheless, the observed cases had very adverse consequences.For example, the failure of these facilities in the Bam Airport Terminal and particularly its control tower resulted in the interruption of the airport operation for several hours. It could be understood from Figure (45) that some of electrical facilities and control equipments have malfunctioned because of the high shock of the earthquake resulted in their operation interruption. A sample of damage to the electrical facilities of the airport is shown in Figure (46). The main reason of this damage has been the failure of supporting structure (the false ceiling).

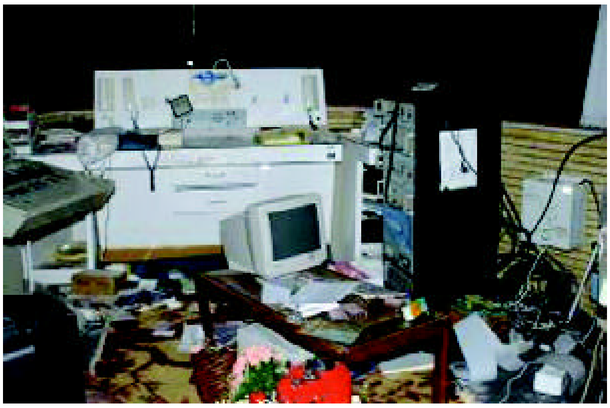

Figure 45. The failure of mechanical and electrical facilities and interior equipment of the Bam airport control tower (Photo Source: http://www.irna.ir/melli/bam/photo_index6.htm)

Figures(47) and (48) show some samples of damage to the electrical facilities. Figure (47) shows the failed light fixtures in the office building of the city electric power substation. The main reason behind this failure is the weakness of connections. Other case of damage to electrical system is shown in Figure 48, which depicts the pull out of the protective tubes of electric wires in the office building of the city electric power substation. The main reason behind this kind of failure seems to be the potential weak lines in the finishing due to the presence of the wire protection tubes, which are in fact some mainly hollow spaces. The partial failure of the ceiling in Figure (48) is also notable. This has been in fact an inspection access window, which has detached form the ceiling again because of weak connection.

As in many of the past earthquake this event had also some cases of post earthquake fires, which were mainly due to the damage to the electrical facilities. Figure (49) shows a partially burnt shop, which caught fire because the failure of its electrical facilities. The fire caused of the deformation of the broken glass pieces as shown in Figure (50).

Figure 46. The failed smoke detector of the Bam airport (Photo by M. Hosseini).

Figure 47. The failed light fixtures in the office building of the city electric power substation. (Photo by M. Hosseini).

Figure 48. The pulled out protective tubes of electric wires in the office building of the city electric power substation (Photo by M. Hosseini).

Figure 49. A partially burnt shop which got in fire because the failure of its electrical facilities (Photo by M. Hosseini).

Figure 50. The deformed pieces of glass due to the fire occurred in the shop shown in Figure (49) (Photo by M. Hosseini)

4.3. Interior Equipments

Several kind of the interior equipments were damaged in the Bam earthquake as shown in Figures (51) to (53). Figure (51) shows the semi fallen blackboard of a classroom, that obviously have had weak connection to the wall. However, it should be noted that even if it had a strong connection (a bigger nail or hook), still, because of the inherent weakness of the wall finishing and even the wall masonry, it would have detached from the wall because of notching phenomenon. The same weakness problem can be seen in Figure (52) which shows the toppled shelves of a shop. The fallen part of the gypsum finishing of the ceiling at the right corner in Figure (51) is notable, as in the safety rules, which should be followed inside a building in the time of earthquake, corners are usually suggested as the safer locations comparing to the other places in a room. The partial failure of the upper part of the wall on the right in Figure (52) is also notable. Figure (53) shows the entirely messed interior equipments of another shop in which the collapse of the stone veneer of the left wall is also visible.

Figure 51. The semi-fallen blackboard due to the weak connection (Photo by M. Hosseini).

Figure 52. The toppled shelves of a shop board due to their weak connection (Photo by A.S. Moghadam).

Figure 53. The entirely messed interior equipments o f a shop (Photo by M. Hosseini)

5. Discussion and Recommendations

By paying attention to the various patterns of damage to the nonstructural elements, presented in the previous section, some facts can be realized, and based on some of these facts some recommendations can be made:

- The directivity effect was quite noticeable in the Bam earthquake, as in many cases of two similar walls or parapets in a building one had completely collapsed, while the other one has survived almost intact.
- The weakness of non load-bearing masonry walls (either exterior or interior), and particularly their weak connections to the main structure was quite evident. Therefore, it is necessary to provide some reliable connections between the walls and partitions and the main structure of the building. This problem is critically important when the wall is supposed to act as and active infill. It can be claimed that many of the framed building failures have been due to the collapse of their infills before the failure of the frame structures. Even if the wall is supposed not to contribute to carrying of the lateral load, still it should be attached in a clever way to the structure so that while isolated from the lateral load bearing system, it can remain in its place, and particularly it can withstand the out of plane loads acting on it.
- The yard walls, which are supposed to carry just their own weight, should also have enough lateral resistance. This can be provided by some vertical ties which anchor the wall to its foundation (the wall should have a suitable foundation anyway), or by closely spaced buttresses [loghaaz-haa].

- Facade, particularly the large stone plates and the 3*cm* bricks, should be securely attached to the corresponding walls. A notable point in this regard is that a group of small tiles or bricks, stuck to the mortar behind them, make it possible to retrofit these kinds of facade with a reasonable amount of supporting ties system, by an external structure.
- Glass façade should be also made safe against earthquake. This can be done in three different ways: 1) using the shatterproof glasses, 2) using some kind of very soft materials around the glass plates in their frames to accommodate their movement without breakage, and 3) using an overall framed structure for the whole glass facade and putting it on a rocker-roller supporting system.
- The parapets and tablets or bill board should have reliable supporting structure securely attached to the main building structure. If the use of light weight materials is encouraged in the country vulnerability of these kind of attachments will be greatly reduced.
- The interior veneers and finishing should be also securely attached to their corresponding walls. It is suggested that the use of integrated sheet veneers is encouraged. This will decrease the vulnerability of the interior veneers to a great extent.
- The connecting methods of the interior equipments to the main structural elements or other parts of the building, recommended or suggested by other countries, including the *US*, are not appropriate for the Iranian buildings, particularly in the cases of concerning the masonry walls. This returns back to the inherent weakness of walls masonry mentioned in section 4 of the paper. It is suggested that these equipments are attached to the walls by some kind of ties which can pass through the wall and can be secured in the other side of the wall.
- Staircases and penthouses are among the most vulnerable nonstructural elements in Iranian buildings. It is suggested that the supporting structure of stairs is prevented from contri bution to carrying of the lateral loads. This will help not only the structural system to have a more reliable seismic behavior, but also the staircase itself to sustain less damage.

6. Conclusions

Based on the matters discussed in the previous sections of this paper it can be concluded that:

- ❖ Almost all of the nonstructural elements in the existing building of the country are moderately to highly vulnerable to the probable future arthquakes. Therefore, the retrofit of these elements is a necessity parallel with the retrofit of the structural systems of the existing buildings.
- ❖ Infill walls and staircases are the most vulnerable architectural elements. It is strongly suggested that these elements are separated from the lateral load bearing system of the building.
- ❖ The connecting methods of the interior equip ments to the structural systems, recommended by other countries, including the *US*, are not appropriate for the Iranian buildings, particularly in the cases concerning the masonry walls. Some appropriate methods, like the one mentioned in section 5 can be developed.
- ❖ The proposed recommendations are useful aids for completion and modification of the third volume of the present "Guideline for Seismic Retrofit of the Existing Building" which is now under revision by the *IIEES*.
- ❖ The use of lightweight materials and integrated sheet veneers should be encouraged in the country. This will be a very effective way for reducing the seismic vulnerability of these nonstructural elements.
- ❖ Some of the suggestions and recommendations, discussed in the paper for retrofit of the nonstructural elements need new research projects, particularly the experimental ones, to achieve the reasonable solutions.

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