Technical Note:

A New Method for Reducing Earthquake Casualties in Poor Performance Masonry Buildings

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Abstract: *The objective of this paper is to present a new method for protecting the lives of residents in catastrophic earthquake failures of unreinforced masonry buildings by introducing some safe rooms within the buildings. The main idea is that occupants can seek refuge within the safe rooms as soon as the earthquake ground motions are felt. The information obtained from the historical ground motions happened in seismic zones around the globe expresses the lack of enough safety of masonry buildings against earthquake. For this potentially important reason, an attempt has been made to create some cost-effective seismic-resistant areas in some parts of the existing masonry buildings, which are called safe rooms. The practical method for creating these areas and increasing the occupant safety of the buildings is to install some prefabricated steel frames in some of their rooms or in their halls. These frames do not carry any service loads before earthquake. However, if a near field seismic event happens and the load bearing walls of the building destroy, some parts of its floors, which are in the safe areas, will fall on the roof of the installed frames; consequently, the occupants who have sheltered in the safe rooms will survive. This paper expresses the experimental and theoretical work executed on the steel structures of the safe rooms for bearing the shock and impact loads. Finally, it was concluded that both the strength and displacement capacity of the steel frames were adequate to accommodate the distortions generated by seismic loads and aftershocks properly.*
Keywords: *earthquake, masonry building, casualties, safe room, steel frame, vibration.*

1. Introduction

Catastrophic earthquakes appear in the headlines with discomforting frequency, causing thousands of lives to be lost specially in masonry buildings. This truly global phenomenon has begun to be understood, and considerable emphasis is being placed on the analytical studies supported by experimental studies both in the laboratory and in the field in an effort to prevent much of this loss of life. It is worth noting that brick masonry has been used as a load bearing material for centuries. In gravity structures constructed by this material, the level of gravity stresses are low and the factor of safety against compression failure is high [1]. Moreover, there is no need for high technology to construct masonry buildings; as a result, they are not expensive. Because of these advantages, the masonry buildings constitute a large portion of the building stock in the world. But masonry structural elements can not resist earthquake effects because their bond tensile strength is too low [2-7]. This is the common problem and the wide-spread concern of structural engineers and building officials, as well as owners, lenders and insurers especially in areas of high seismicity.

The term repair means restoration of the strength, stiffness and deformation capacity of structural elements that have been damaged. Any repair or strengthening of an existing structure varies from case to case depending on the specific situation which needs to be considered [8]. Also, solutions to strengthening problems require a high degree of individual attention to detail and there is a wide range of expensive choices in the fields of design and construction. In other words, strengthening of the existing structures is an expensive and time consuming process.

Safe room is the name of a new method, which is regarded as economical and practical, and it can be used for lowering earthquake life losses in masonry buildings. In this method, some safe areas having a good balance of safety versus cost will be prepared inside the building and the existing load carrying system of the structure will not change. The practical method for making these safe areas inside a building is to introduce some prefabricated moment resisting steel frames there. These one-story, one-bay steel frames are characterized by rigid connections between the beams and columns that force the entire frame to deform when subjected to lateral loads. Regarding architectural restrictions, the size of the structural elements should be as small as possible. For this reason, the ordinary safety factors suggested by different structural building codes like AISC [9] should be lowered. On the other hand, safe room is the last place for saving the lives of residents during earthquake excitations and it should not collapse. Due to the lack of code guidance on these types of structures, the size of entire steel elements of the safe rooms are chosen according to a lot of full-scale tests. This paper presents the results of the experimental work executed in this field. Also, the results of the analytical work are compared with the ones obtained from the laboratory.

2. Safe room

The ultimate goal for introducing safe room is to protect human lives at the time of earthquake. Because many of the existing masonry buildings do not contain vertical and horizontal tie beams and also their load bearing walls in plan are not enough, they may destroy when subjected to earthquake ground motions. Year of construction, construction procedure, building stiffness, and the amplitude of ground motions are the key factors here. The older the building is, the more likely it is that local or global collapse will occur. In the method presented herein, some parts of the poor performance building, which are called safe rooms, will be strengthened by introducing some prefabricated steel frames within them. It is worth noting that all the steel frames in different floors should be positioned concentrically. There is no stress inside the elements of the frames caused by the weight of the masonry building. Indeed, after an earthquake and the destruction of the load bearing walls, these frames will carry the weights of the floors over them. As a result, after sensing foreshocks, the occupants who are trained to go to the safe areas urgently will survive and the seismic risk will be reduced.

To install the steel frames of safe rooms quickly and also to improve the quality control of the welding, a prefabricated system is utilized in this research. To have a performance-based design and to see safe rooms in reality, some full-scale prefabricated steel frames were constructed in a factory and they were assembled in different masonry buildings. Box elements were used for all the columns and beams of the frames. According to the results of other investigators, the responses of box elements under different dynamic loads are predictable [10-13]. Because the sizes of box elements were chosen in a way that they were able to move inside each other, the dimensions of the frames could alter in their plans and elevations; therefore, the prefabricated steel frames could fit quite well in rooms with different dimensions.

Baker et al. have introduced a similar shelter for saving the human lives against bomb explosions [14]. This shelter, which is like a table, is capable of accommodating a family of two adults and two children in such a way that if the house collapses completely, due to a near miss from a large bomb, the occupants will not be crushed by the derbies and will be able to escape or be rescued in a short time.

3. Structural analysis issues

Simply defined, structural analysis is a mathematical process by which the engineer verifies the adequacy of the structure with respect to its strength and stiffness. It is not always possible or necessary to obtain rigorous mathematical solutions for engineering problems. In fact, rigorous analytical solutions can be obtained only for certain simplified cases. Most other practical engineering problems, involve complex material property, loading, and boundary conditions. The engineers introduce assumptions and idealizations deemed necessary to make the problem mathematically manageable, but still capable of providing sufficiently accurate solutions and satisfactory results from the point of view of safety and economy. They establish a link between the real physical system and the mathematically feasible solution by providing an analytical model, which includes all the assumptions imposed on the physical problem. Modeling techniques, therefore, can be defined as a way to reduce, synthesize, and properly represent the structural system.

As a result of gravity, the weight of the building itself imposes loads on the structure called dead loads, which remain constant for the life of the building. Occupancy loads also impose gravitational effects, which vary because of the changing occupancy of the floors. These are called live loads and include the effect of people and furniture. In this research, the total gravity load of the existing floors, which is a design parameter estimated by the designer, is assumed to be 833 kg/m^2. The dimensions of the one-storey one-bay steel frame of the safe rooms are 3×4 m^2 in plan and 3 m in height. Three frames have been designed for carrying the load of one, two and three floors. It is worth noting that these steel frames do not carry any service loads before earthquake, and after demolishing the building by a devastating earthquake, they start working. Also, after evacuating the safe rooms the main duty of the steel frames will finish. Therefore, it is logical to lower the safety factors presented by the ordinary building codes in this case.
This part of the paper focuses on the analytical results of the steel frame, which carried the load of three floors. The following two load conditions were considered for the frame: The entire load was uniform and it was applied on the roof of the frame; The load of the floor, which was over the frame, was applied on the roof of the frame as a uniform load and the other floors imposed their weights from the columns of their own frames to the studied frame. These four point loads of the second load condition were applied on the four corners of the roof of the studied frame.

Figures 1 and 2 have been extracted from analyses; these figures can be used for comparing the stress ratios of the two load conditions above. Figure 2 shows the maximum stress ratio of the column was 1.5 and figure 1 illustrates this ratio was 4.02, which means the maximum stress imposed to the columns was about four times the allowable stress. The maximum stress ratios of the beams were 1.45 and 4.34 in figures 2 and 1 respectively. Consequently, the stress ratios of both the columns and beams were

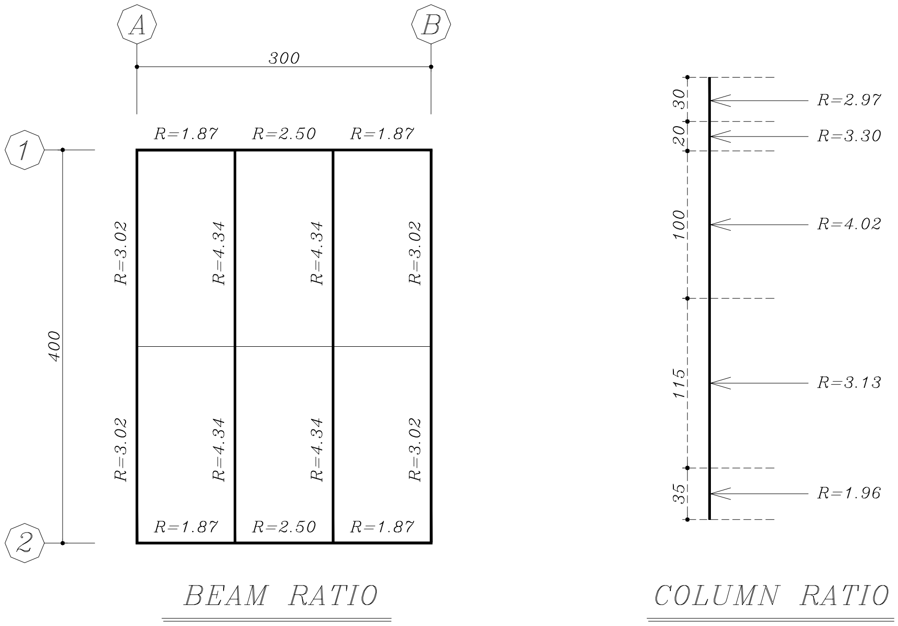

Fig.1 Stress ratios of the steel frame under uniform load (q=2.5 ton/m^2)

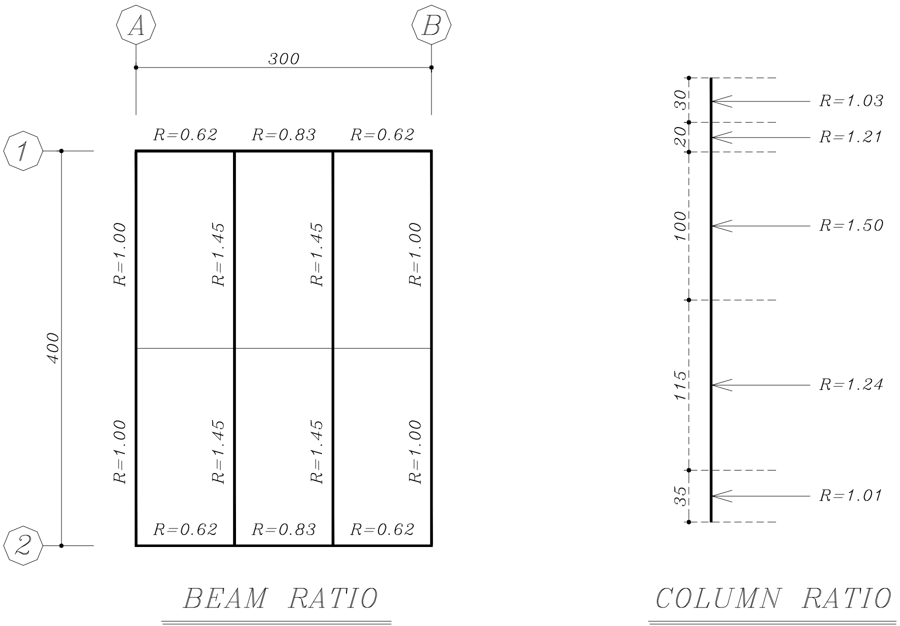

Fig.2 Stress ratios of the steel frame under both uniform and point loads (q=0.833 ton/m^2, p=5 ton)

Fig. 3 The collapsed initial steel frame under a gravity load of 30,000 kgf

more critical in the first load condition. As a result, this load condition was chosen for the experimental work. The difference between the stress ratios of the first load condition (figure 1) and the second one (figure 2), which is the real load condition, is considered as the margin of safety for considering the detrimental effects of impact loadings, nonuniform settlements of the supports in the event of an earthquake, and aftershock effects indirectly.

4. Laboratory testing

In this part of the paper the results of some full-scale tests are presented. The main objective of these experimental investigations was to enhance the load carrying capacity of the system without increasing the expenditures considerably. It is worth noting that more than 60 tests of full size were conducted to upgrade the steel frames and to control their plastic collapse mechanisms. Before conducting these tests the steel frames fractured at load and deformation demands well below those of which they were intended. The nominal yield and ultimate strengths of the steel elements were F_y=240 MPa and F_u=370 MPa respectively. All the connections were welded using E60-13 electrodes for a duration of 3 to 4 seconds at 250 A.

4.1. Slender columns

One of the initial frames was subjected to the uniform gravity load of 2.5 ton/m^2 simulated by gravel bags (50 kgf each). At the beginning, the frame carried the load properly. However, a few hours later, the columns collapsed from their midheight as shown in figure 3. This kind of destruction was desirable because the assumed people underneath the steel structure had a chance of survival.

After finding this weakness, the middle parts of all the columns were strengthened to improve the internal force transfer mechanism of the structure. The strengthened structure did not collapse again. It should be mentioned that the structure carried not only the 2.5 ton/m^2 uniform load but also a 20 ^{o}C temperature variation during the first 11 days. According to the analytical work (figure 1) the maximum stress ratio of the column was 4.02 i.e. about four times the allowable stress. In other words, the analytical results do not validate those obtained experimentally; it means,

Fig.4 Shifting the place of the plastic hinge

information regarding the load bearing capacity of slender steel columns under eccentric loading is limited and it should be studied further. It is worth noting that a comprehensive research has been executed on slender concrete columns carrying eccentric loads recently [15]. The result of the research shows the lack of exactness of the existing methods for measuring the ultimate load bearing capacity of slender high-strength concrete columns.

4.2. Column hinging mechanism

Some experimental and analytical researches have been done on the destruction modes of steel structures [16-21]. It is generally accepted to use a strong-column weak-girder philosophy in seismic zones. In fact, beams collapse locally and before columns in this system; this local failure helps the designers meet desired performance goals because global collapse is unlikely to occur. In other words, strong column, weak beam structures are preferred since they avoid the concentrated seismic damage that occurs in weak column systems. To assure strong column, weak beam behaviour , the plastic bending resistance of the columns should be greater than that of the beams.

At the beginning of this research the strong-column weak-girder system was utilized. But the results obtained from the experiments employed to evaluate this system were not acceptable because the steel frames collapsed in a way that there was no chance of survival for the assumed occupants sheltered under the frames. However, according to figure 3 the opposite system collapsed in a much better way. As shown in this figure, after the intentionally destruction of the steel frame from the columns, about 50% of the safe area remained almost safe. It means, even after collapsing the frame, the people underneath it had a chance to survive. Hence, the column hinging mechanism is accepted in this study for the steel frames of safe rooms.

To avoid instability problems, particularly in the inelastic range, adequate stiffness and restraint must be provided. In fact, each column should have a reserve of compressive strength for additional flexural and overturning compression that may arise from earthquake forces. As shown in figure 4, a secondary element could change the plastic collapse mechanism of the column, which could increase its compressive strength. It is clear that the plastic hinge has been shifted from the beam-column interface to the column immediately beneath the secondary element. In other words, the plastic hinges of

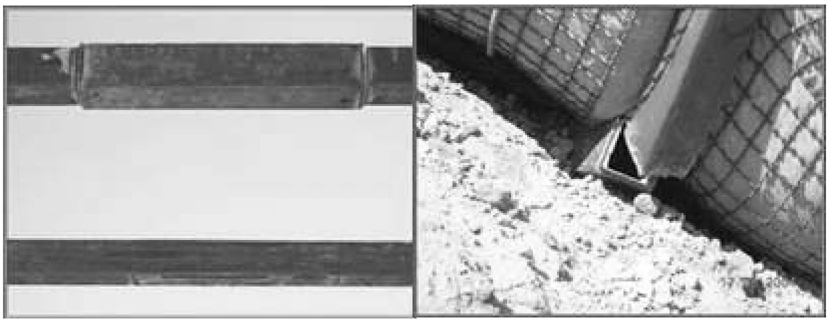

Fig.5 Welding the two ends of the stiffening box element

Fig.6 Changing the direction of welding

the elements can be transferred to the desired locations by strengthening some parts of them. Accordingly, the upper parts of the columns were strengthened by four stiffening box elements.

4.3. Welding details

Although correct welding is necessary, poor workmanship and inadequate welding details can produce poor performance regardless of the welding procedure. In other words, the design and detailing for successful welded construction require consideration of factors which include, but are not limited to, magnitude, type and distribution of forces to be transmitted, accessibility, restraint to weld metal contraction, thickness of connected materials, effect of residual welding stresses on connected material and distortion.

For example, according to figure 5, the temperatures associated with the welding process of the two ends of the stiffening box element reduced the strength of the main beam and manifested into tears. Figure 6 shows the effect of changing the direction of welding on the performance of elements. It is clear that changing the welding direction was quite effective for disappearing this weakness point of the steel frame.

4.4. Beam to column moment connections

Rigid connections are those with sufficient stiffness to hold the angles between members virtually unchanged under load. A frame that consists of such connections is defined as a rigid frame or an unbraced frame. It gets its strength and stiffness from the nondeformability of joints at the intersection of columns and girders. Rigid frames generally consist of a rectangular grid of horizontal

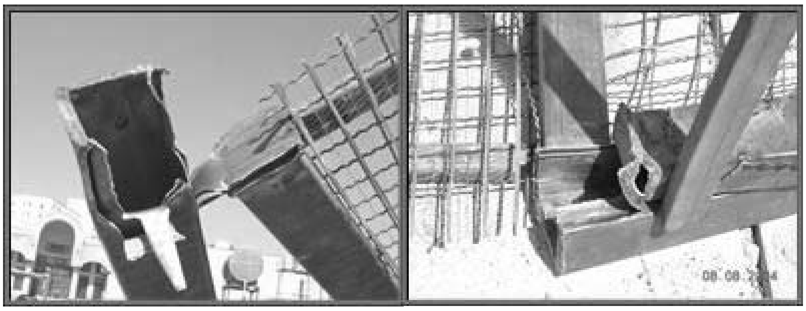

Fig.7 Destruction of beam to column moment connection

Fig.8 Using end plates and dowel plates in beam to column moment connections

beams and vertical columns connected in the same plane by means of rigid joints. Because of the continuity of members at the joints, the rigid frame responds to lateral loads primarily through flexure of beams and columns. This continuous character of the rigid frame is dependent upon the rotational resistance of the connections not to permit any slippage.

While thousands of moment frame buildings were being constructed, limited testing of the connection and further refinement of the connection details continued. Although some problems were noted in the laboratory performance of the connections [22,23], most engineers and researchers continued to trust the connections would perform as intended. However, the engineering community has to consider the implication that there would be widespread cracking of moment frame buildings in an earthquake with skepticism [24]. As shown in figure 7, in this research, the beam to column connection was an important weakness point of the structure. To solve this problem, the tops of columns were strengthened by four end plates (figure 8). These plates enhanced the gravity load carrying capacity of the frame about 460 kgf/m^2. In other words, introducing a suitable rigid connection detail is one of the most important duties of the structural design

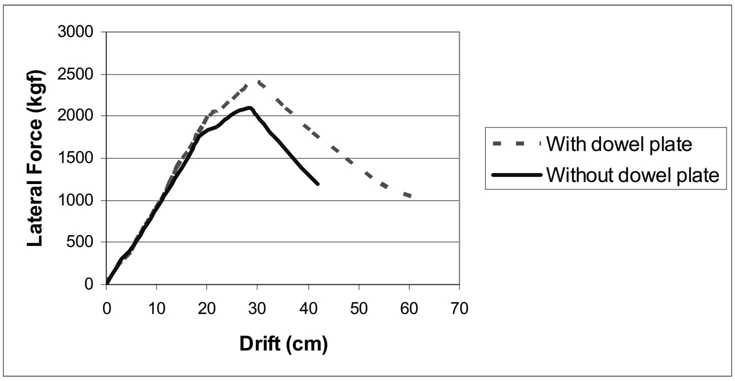

Fig.9 Effect of dowel plates on pushover diagram

engineers.

4.5. Increasing the flexibility

In earthquake-resistant design, it is not sufficient to make a member "strong". It must also have a reserve of ductility. In fact, ductile materials are highly desirable for earthquake-resistant design because earthquake design should satisfy the following basic objectives: to prevent loss of life and serious injury and to prevent buildings from collapse and dangerous damage under a maximum intensity earthquake; to ensure buildings against irreparable damages under moderate to heavy earthquakes. The strength built into the structure alone cannot create an earthquake-resistant design. Earthquake resistance requires energy absorption, which means the structure should have predictable ductility as well as strength. The ductility of the structure can be visualized as its capacity to undergo large deformations without appreciably losing its load-carrying capacity. If such a ductility is present, the building is prevented from collapse even if it is seriously damaged. Therefore, in addition to seismic strength design, the ductility of the structure should be given due consideration.

The required ductility can be achieved by proper framing and connection details. Because of the increased emphasis placed on ductility, the researchers decided to add some dowel plates in the beam to column connections (figure 8). Figure 9 shows the effect of these plates on the flexibility of the steel frame. The lateral load versus lateral displacement graph reveals that the roof drift ratio (lateral displacement at the top divided by the total height) and energy absorption capacity of the system improved about 50% after choosing this connection detail.

4.6. Corbel effects

The panel zone can be defined as that portion of the frame whose boundaries are within the rigid connection of two or more members with webs lying in a common plane. It is the entire assemblage of the joint at the intersection of moment-connected beams and columns. It could consist of just two orthogonal members as at the intersection of a roof girder and an exterior column, or it may consist of several members coming together as at an interior joint, or any other valid combination. In all these cases, the panel zone can be looked upon as a link for transferring loads from horizontal members to vertical ones and vice versa.

Corbels can be used for decreasing the

Fig.10 Using corbels for strengthening the connections

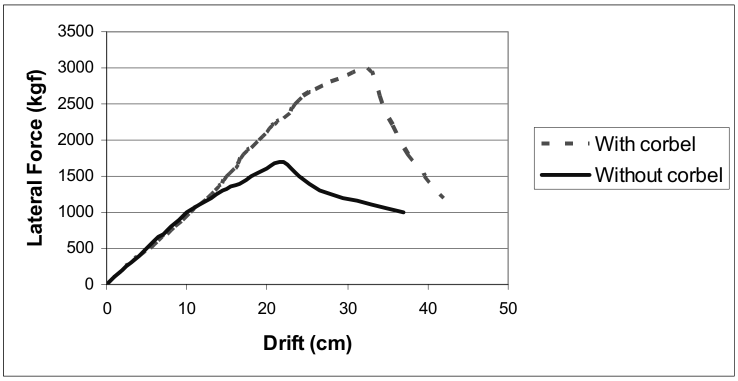

Fig.11 Effects of corbels on pushover diagram

internal stresses of panel zones considerably and, therefore, enhancing the ultimate strength of the structure. Accordingly, the authors decided to use some corbels for improving the lateral load bearing capacity of the system (figure 10). Figure 11 shows the result of this decision. It is clear that the corbels improved both the lateral load bearing capacity and energy consumption of the system about 100%.

5. Conclusions

Conclusions drawn from the material presented in this paper may be summarized as follows:

The idea of safe room is a practical solution for lowering the earthquake casualties of poor performance masonry buildings located in earthquake-prone areas.

The column hinging mechanism should be utilized for the structures of safe rooms. In fact, after the intentionally destruction of the steel frames from the columns, about 50% of the safe areas remain almost safe.

Corbels can be used for increasing the lateral stability of steel structures in seismic zones because they decrease the internal stresses in the panel zones of rigid frames considerably. The pushover diagrams of the final structural systems of the safe rooms showed that the ductility and lateral stability of the systems were quite satisfactory and the structures could accommodate the distortions generated by seismic loads and aftershocks properly.

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