A Thought Generated from the Recent Wenchuan Earthquake in China - Proposing a Low Cost, Total Collapse Reduction Design for Old Reinforced Concrete, Low-Rise Buildings that Are Not Required by Law for Retrofitting

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ABSTRACT

The recent May 12, 2008 Wenchuan Earthquake in Sichuan, China had toppled a number of low-rise concrete structures. Most were general residential buildings; however, some were school facilities. Death tolls are tragically high. It is learned that majority of these buildings were older concrete structures. Older concrete construction has been known for its lacking ductility and prone for sudden failure or total collapse. Older concrete building is difficult and very expensive to be upgraded to the desired level of seismic capacity prescribed by the modern concrete building codes. Unfortunately, most home owners would opt not to retrofit unless it is specifically dictated by the governing laws or codes.

This paper focuses on two areas: 1) Reviewing one of the best known fiber reinforced polymer (FRP) practice used for retrofitting old reinforced concrete (ORC) and un-reinforced masonry (URM) buildings in USA. 2) Proposing a new concept, utilizing FRP material, for strengthening the ORC or URM buildings. The new strengthening strategy, however, is focused specifically on reduction of death tolls/injuries caused by the collapse of the earthquake stricken ORC/URM buildings. An exemplary five-story low-rise ORC/URM building is conceptually developed for the purpose of illustrating the new concept on strengthening such old buildings.

KEYWORDS: earthquake protection, fiber reinforced polymer, un-reinforced masonry building.

1. BACKGROUND

When a strong earthquake strikes the area where it has a large number of ORC/URM buildings, chances are that majority of these buildings would fall or pancake down during the shaking. Sudden collapse has been seen in various seismic prone regions such as, China, Taiwan, Mexico, Turkey and Greece, etc. Tragically, whenever a major quake hits such region, the number of death tolls is tremendously high and the economic power impacts are unbearably huge; furthermore, the economic recovery time and effort required for such disaster are painfully long (Figures 1 & 2).

There have been various structural materials and systems developed by adding special steel frame braces and/or reinforced concrete shear walls, or, strengthening the existing walls as the ways for structurally upgrading the ORC/URM buildings (References 1 & 2). Employing base isolation, supplemental energy dissipation and structural control, etc. are the more recent strengthening concepts used in constructing the low-rise reinforced concrete (RC) buildings. The challenges for designing a new and/or retrofitting an existing low-rise residential RC buildings are in finding adequate locations and/or ample rooms for placing the new frames or shear walls, and, providing adequate horizontal diaphragm length required between the new frame and the existing floor for lateral loads transfer. A new concept on designing a new low-rise RC building with multilocalized seismic isolators is also being studied by the author at the University of Oklahoma for better seismic performance (Reference 3).

Figures 1 & 2 – Earthquake collapsed concrete buildings in Wenchuan, China, May 12, 2008
(Photos taken from http://xfj.zunyi.gov.cn/cms/cms/website)

2. USING "FRP" AS STEEL AND CONCRETE

An innovative approach that has been developed in seismic retrofitting industry is to use the fiber reinforced polymer (FRP) to strengthen the ORC/URM buildings. Using FRP for seismic retrofitting applications, however, has been mainly utilized in strengthening the URM walls and the ORC columns. It has encountered difficulties on applying the FRP to the existing slabs and beams. The difficulties mainly are centered on the debonding; air trapping, etc. experienced. The American Concrete Institute in U.S. had also generated a state-of-the-art report on FRP application for concrete structures early in 1996 (References 4, 5 & 6). It is recognized that any application of FRP in seismic strengthening the URM walls and the ORC columns should be performed by the specialized professionals, such as the QuakeWrap, Inc. in U.S. (Reference 7)

The FRP manufacturers, e.g., Fibergrate Composite Structures Inc. and Strongwell Corporation in U.S. (References 8 and 9), have produced numerous structural shapes such as, "I", "square tube", "circular tube", "plates", etc., for lighter structural applications in building industry.

Figures 3, 4 & 5 – FRP seismic strengthening applications on walls, columns and beams
(Courtesy photos from QuakeWrap, Tucson, AZ, USA)

Stongwell Corporation had also pultruded larger section, called “double-web I” or “modified box” beams in which two vertical webs are connected by a flange across the top and bottom. Such larger structural section, manufactured through complex phenolic resin process and a vinyl ester resin system, is suitable as replacement for steel and concrete used in bridge and building construction because of its high shear, bending and stiffness properties (Reference 10).



Figures 6, 7 & 8 – Examples of high strength FRP applications in building construction
(Courtesy photos from Strogwell Corp., Bristo, VA)

Composite materials such as FRP using glass and/or carbon contents have been widely used for many decades in various industries, e.g., auto, ship, aircraft, oil refinery, furniture, etc. industries. Because of FRP’s superior properties such as, high strength, light weight and variable color choices, etc., the author proposes an innovative new way of thinking on seismic protection design for life saving only, and, presents an idea of using the FRP materials to build new life-protecting structures integrated with the existing residential ORC/URM buildings for possible collapse caused by the strong earthquakes.

3. A NEW CONCEPT - ORC/URM BUILDING COLLAPSE CONTROL DESIGN

In Japan, earthquake drills are carried out routinely and rigorously in elementary schools training children be calm and hide themselves underneath their desks for minimum protection during the instant when a strong earthquake strikes. By doing so, this will protect them from being seriously injured or killed by the heaving falling objects.

ORC and URM buildings are often viewed as economically and/or physically not feasible neither for wholesome seismic upgrading nor total demolishing and constructing a new one. In California, United States, for example, the government and the local building codes demand that public or commercial ORC and URM buildings be upgraded to withstand certain prescribed earthquake levels or ground motions according to the local building codes, however, private residential homeowners often opt not to structurally upgrade their ORC/URM buildings because these buildings are not subject to seismic retrofit as required by the local building codes.

3.1 Localized Secondary Add-on FRP Structures

Recognizing the devastating reality of massive number of low-rise ORC/URM buildings that are existing in many earthquake prone regions and can not be demolished because of the economical and/or legal restrictions, this paper presents a strategic compromise, i.e., a brand new concept, by developing a series of localized secondary add-on FRP structures as the back up defense system to control the collapse sequence or prolong the collapsing time span , thus, increase the chances of saving innocent lives and minimize earthquake caused human tragedies.

3.2 Preliminary Sizing the Joist Element of the Basic Add-on FRP Structure

Basic beam element model can be depicted from the simplified add-on FRP structures modeled with the postulated collapsing ORC/URM building shown in Figures 9. The third model counting from the left illustrates how the localized secondary add-on FRP structures, encased in the original structural frames, are interacting within the swayed ORC/URM main frames.

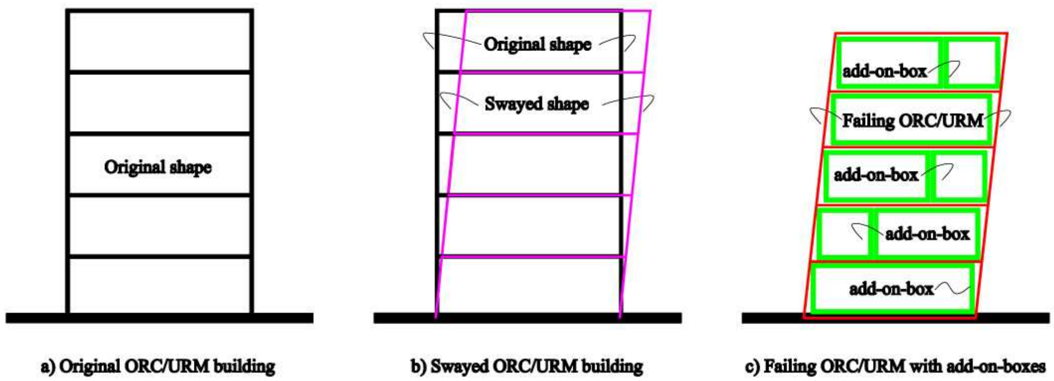

Figure 9 – Depicting the structural collapse stages for building with the add-on structures

An exemplary five-story low-rise ORC/URM building is conceptually developed for illustrating the new concept of installing the light-weight add-on FRP structures made of the high strength FRP structural members. Each add-on box structure consists of a series of prefabricated high strength FRP components that are assembled together according to each individual room's existing configuration. In this study each basic add-on FRP component is engineered with the respective design loads and structural properties assumptions shown in the Table 1 (*).

Roof level	Floor level
Dead Load: 150 psf (733 kg/m^2)	Dead Load: 150 psf (733 kg/m^2)
Live Load: 20 psf (98 kg/m^2)	Live Load: 40 psf (196 kg/m^2)

Minimum flexural strength (LW/CW) = 20,000/10,000 psi (1410/705 kg/cm^2)
Minimum shear strength = 3,000 psi (210 kg/cm^2)
Minimum compressive strength = 7,000 psi (493 kg/cm^2)

Maximum (4+1) levels of total load assumed to be carried per member
Maximum roof or floor joist span length = 15 ft (457 cm)
Maximum roof or floor header span length = 10 ft (305 cm)
Maximum wall studs or post height = 9 ft (275 cm)
Joist size = 4 in x 11 in x 1 in (10 cm x 28 cm x 3 cm); Joist weight = 19 lb/ft (28 kg/m)
Post size = 4 in x 4 in x 1 in (10 cm x 10 cm x 3 cm)
Typical FRP density = 103 lb/ft^3 (1665 kg/m^3)

Table 1 – Assumed basic design loads and structural properties

(*) The SI units in the above conversion of "US units to SI units" is expressed with the "g" factor omitted, for simpler comparison, without bringing the units of "Newton" and "Pascal"

A simple beam model is shown below in Figure 10 illustrating the (4+1) levels load carrying assumptions (see Table 1). It is assumed that there may be a loading case that the 2nd floor's add-on FRP structure may be required to carry a concentrated load from the upper three floor and roof loads accumulated together because of inconsistent partition wall layout. Thus, the 2nd floor joist, spaced at 12 inches (30 cm) on center, will carry the extra concentrated load in addition to the uniform load carried by the 2nd floor joist. The maximum span for the joist is assumed to be less than 30 feet (9 m). The maximum moment found for the 4 in x 11 in x 1 in (10 cm x 28 cm x 3 cm) joist, with minimum allowable flexural strength of 20,000 psi, is reasonable per Reference 9. The shear check can be omitted by inspection.

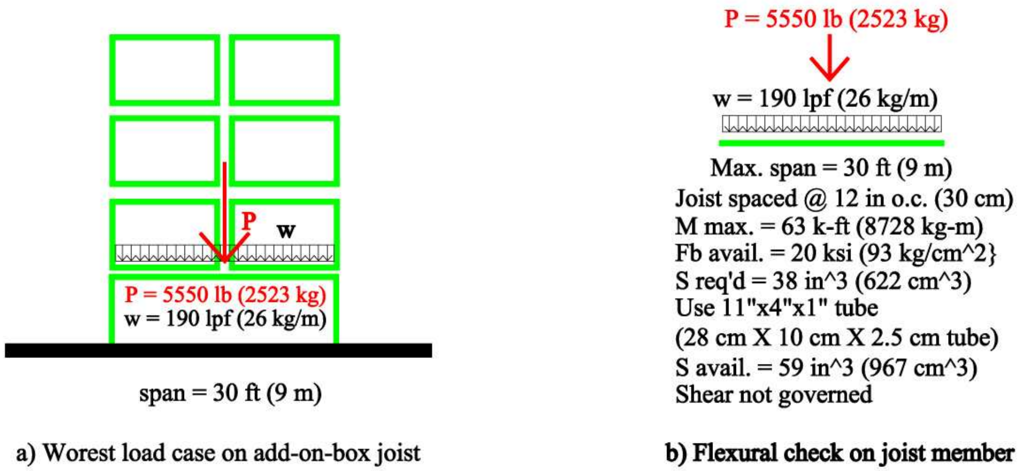

Figure 10 - Simple joist model with postulated governing load case for bending (**)

(**) It should be noted that the preceding conceptual design and its flexural check are based on the "Structural Resistance" concept in contrast to the Load Resistance Factor Design (LRFD) which is a probability distribution of "Load/Stress or Loads".

It should be noted that each add-on FRP structure is to be physically built somewhat smaller than the space/room which is to house the add-on FRP structure in a manner that there will be no more than three inches gap between the FRP structure and the space/room. Thus, the local floor deck or wall will not have more than the three-inch deformation in any direction before its being resisted by the localized secondary add-on FRP structure.

Figures 11 and 12 depicted below are further to show how the bare bone framing and the assembly of the add-on FRP structural components will look like.

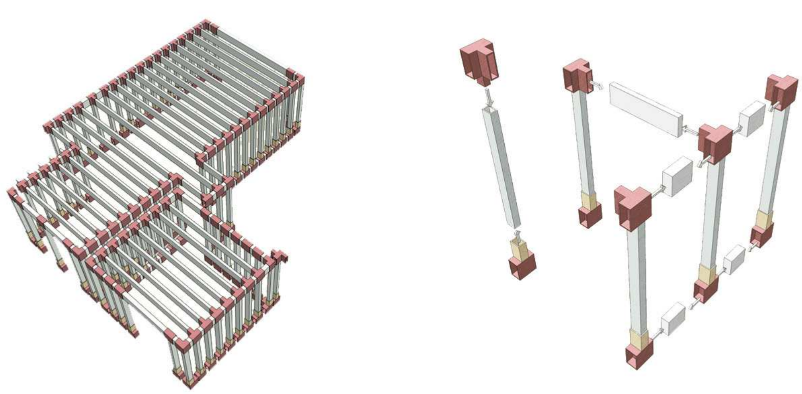

Figure 11 & 12 – Partial perspectives of the bare bone framing and assembly of the add-on FRP components

3.3 3-D Illustration of Add-on FRP Structural Assembly in ORC/URM Building

A typical floor plan shown as a cut-out perspective view for the model building is shown in Figure 13. Meanwhile, a same floor plan view with the addition of add-on FRP structures, installed in the bed room and the living room, is shown in Figure 14 adjacent to the Figure 13 for better illustration on how the add-on FRP structures are integrated in the postulated ORC/URM residential building. It should be noted that there are supposed to have structural FRP plates integrated with the floor joists as well as wall studs respectively. These structural FRP plates are to be placed about three inches below the existing roof or floor deck. For clearer illustration, these FRP plates are omitted in each figure shown below.

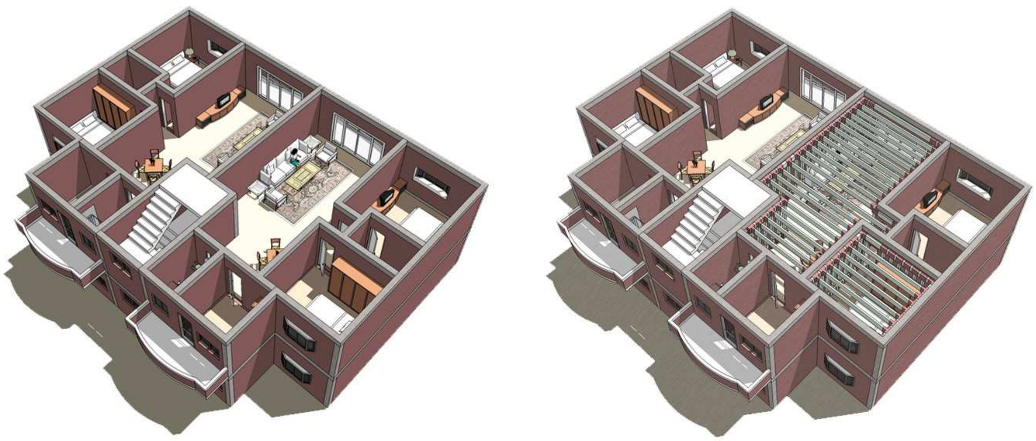

Figure 13 & 14 – Partial floor perspective views: without and with the add-on-box-frames

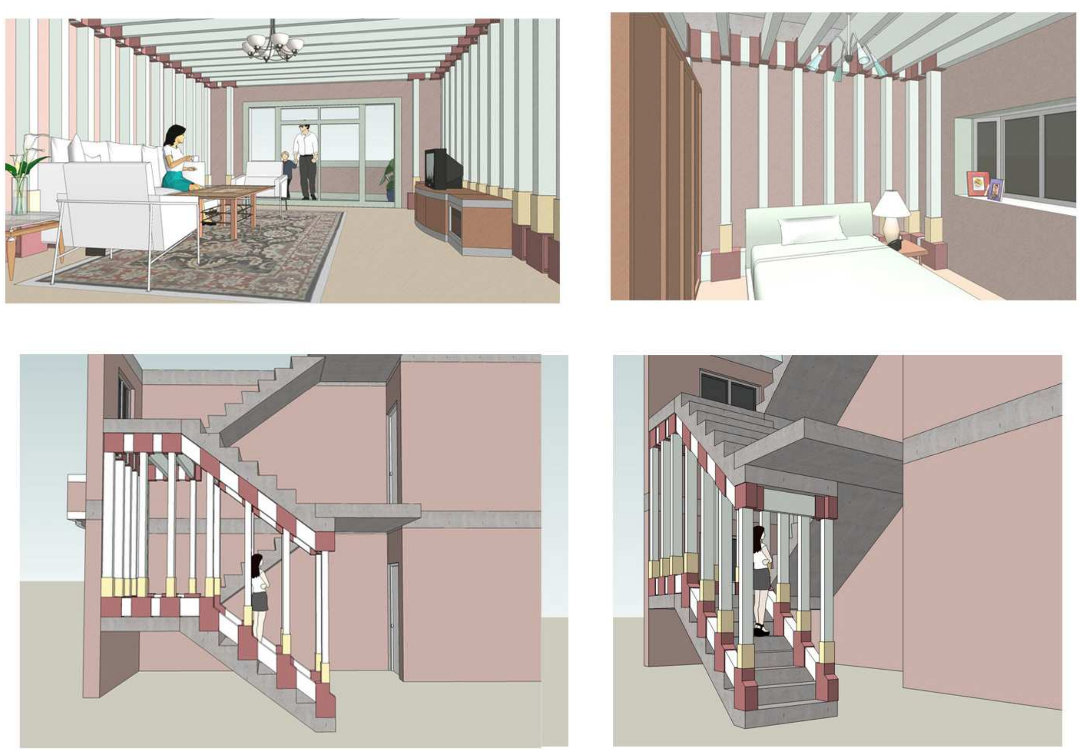

Figure 15, 16, 17 & 18 – Perspective views of family room, bed room & staircase with the FRP add-on structures

Additional renderings on living room, bed room and staircase are presented in Figures 15, 16, 17 & 18. It needs to be reminded that, for clarity reason, only the part of the single level add-on structures is shown in each rendered drawing.

It can be seen, from Figures 15 through 18, the add-on FRP structures will not only provide safety protection but also can contribute the interior enhancing effect, i.e., the add-on FRP structures can make the proposed seismic protection concept extremely attractive to the homeowners as well as the FRP manufacturers for pursuing.

5. CONCLUSIONS

The secondary localized add-on-box FRP structures are made of high strength and light weight reinforced polymer materials; they can help lengthen the structure collapsing time, thus, increase the chances of saving innocent lives and minimize human tragedies. The add-on FRP structure is easy and inexpensive to assemble, and, it creates minimum disruption to the daily household activities during the alteration. Furthermore, the add-on FRP structure can be colorful per architectural specifications.

There are a series of continuing research efforts must be pursued in order to verify the validity of the add-on FRP structural concept. Future preliminary listings of studies are suggested below.

1) Analytical study:

a) To pursue full exploration and development of the architectural/structural prototypes for the add-on FRP structural components and its cost feasibility.
b) To perform analytical model development and computer analysis for the investigation of "delayed progressive collapse stages study and the structural interactions between the ORC/URM main structures and the add-on FRP structures".

2) Experimental Study:

a) To fabricate and conduct the non-destructive tests on scaled models.
b) To construct full scale tests on the FRP members and components.
c) To conduct full scale model tests on ORC/URM building with the integration of the add-on FRP structures.

Since the College of Architecture at the University of Oklahoma has the capability for structural model making, it is desirable that the above future tasks would be pursued with collaborative support from interested manufacturers.

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