Comparative Vulnerability Assessment of Retrofit Techniques for Pre-Code RC Structures

A.M. Mwafy[*] & S. Elkholy[+]
United Arab Emirates University, PO Box 17555, Al Ain, UAE

15 WCEE
LISBOA 2012

SUMMARY:
This study aims at selecting an effective retrofit technique from a number of alternatives for mitigating the anticipated seismic risk of the pre-code school building stock in a medium seismicity region. The reference structures are selected based on an extensive survey of the inventory that includes diverse school typologies. Inelastic simulation models are developed for the reference structures using both the fiber-based modeling approach and the improved applied element method to enable predicting limit states and monitoring structural damage. The ground motion uncertainty is accounted for using 20 input ground motions, representing two seismic scenarios. The observed damage from incremental dynamic analyses (IDAs) is described in terms of fragility curves and damage states before and after the application of retrofit solutions. The study illustrates the importance of assessing different mitigation strategies under various seismic scenarios to arrive at an effective solution for the possible implementation at an urban scale.

Keywords: Seismic retrofit, pre-code buildings, fragility relationships, IDA, improved applied element method

1. INTRODUCTION

A large number of buildings in the existing inventory around the world exhibit a risk of poor performance because of the lack of efficient seismic design provisions when they were constructed or due to poor construction quality. The consequences of neglecting this seismic risk are catastrophic, particularly for certain types of structures such as school buildings. This necessitates improving the seismic performance of substandard buildings to mitigate seismic risk. Several seismic retrofit techniques have been proposed to upgrade the seismic performance of substandard buildings. These methods include improving the seismic performance of existing elements or connections and/or adding a new lateral force-resisting system. The retrofit techniques may be also classified as those enhancing capacity and those reducing the seismic demand. The latter approach, for instance the addition of damping devices, is more suitable for regions with high seismic risk. Improving seismic performance involves: (i) strength, (ii) stiffness, (iii) ductility, and (iv) combination. Although strength and stiffness are often controlled by the same element or the same retrofit technique, the two deficiencies are usually considered separately. The retrofit approaches related to strength and stiffness include, for instance, the addition of concrete, steel, or fiber reinforced polymer (FRP) jackets to columns. Since ductility is attributed to inadequate detailing, its retrofit techniques are disruptive and expensive and therefore are not commonly used, particularly in low-to-medium seismic regions. FEMA (2006) discusses in detail the practical and effective retrofit techniques judged to be the most commonly used for different buildings.

The aim of the present study is to assess the seismic performance of pre-code RC buildings and the effectiveness of standard retrofit techniques to mitigate the earthquake losses of the school building stock in a medium seismicity region, represented herein by the Fayoum district, Egypt, for the possible application at an urban scale. Two of the common deficiencies in pre-code buildings due to a design with inadequate seismic provisions are investigated, namely those related to global strength and global

[*] *also affiliated with Zagazig University, Egypt (on leave).*
[+] *also affiliated with Fayoum University, Egypt (on leave).*

stiffness. Detailed multi-degree-of-freedom numerical models developed using both the fiber modeling approach and the improved applied element method (IAEM) are employed to derive fragility relationships using a wide range of input ground motions to provide insight into the anticipated damage before and after mitigation measures.

2. FIELD SURVEY AND SELECTION OF REFERENCE STRUCTURES

Several existing buildings were damaged in Egypt after the October 12, 1992, Dahshur earthquake, since they were designed without adequate seismic provisions. The present study focuses on the assessment of the seismic performance of pre-code (i.e. constructed before 1992) RC school buildings and the effectiveness of standard retrofit techniques to mitigate earthquake losses in the Fayoum district, middle Egypt, which extends for about 6000 km^2 with a total population of 2.9 million inhabitants. The Fayoum town occupies part of an ancient city, which was founded in 4000 B.C. The inventory database was collected using site visits rather than other approaches such as satellite image processing. This enabled collecting important structural information such as the actual building height, irregularity features and soil conditions. The field survey enabled identifying 1416 school buildings and their construction typology. 1334 school buildings are RC frames, while only 82 are masonry. A summary of the data collected from this extensive survey is shown in Figure 1. Detailed information is presented for the Fayoum county, which includes 23% of the total inventory. The school buildings were classified according to construction type, construction date, number of stories, and soil class. It is clear from the survey statistics shown in Figure 1 that the collected database includes most of the school building typologies typically found in medium seismicity regions.

Due to the computationally demanding approach adopted in the present study for developing vulnerability relationships using detailed modeling and analysis approaches, the selection of a representative structural configuration from this extensive database is necessary. A three-story primary school building was therefore selected as a reference structure for the present study, as shown in Figure 1. This school experienced structural and non-structural damage during the October 12, 1992, Dahshur earthquake. The availability of structural drawings and material properties of this school supported this selection. The reference structure represents a typical pre-code school building commonly found in medium seismicity urban areas. The building in plan consists of a number of segments separated by expansion joints. The geometric characteristics and steel reinforcement of different structural members are illustrated in Figure 2. The main lateral force resisting systems are moment-resisting frames. The floor system is solid slab, and the building is founded on silty clay soil. The nominal concrete cube strength is 25 MPa and yield strength is 240 MPa for both longitudinal and transverse steel reinforcement. The framing systems in the longitudinal and transverse directions do not comply with the capacity design concepts of modern seismic codes, and can be described as weak column-strong beam systems.

3. SELECTION OF RETROFIT TECHNIQUES

The present study focuses on enhancing the seismic performance of existing elements rather than adding new elements such as new shear walls or braced frames. The main factors dictated this decision are the effectiveness of the retrofit approach in enhancing seismic performance and availability of labor and material at an acceptable cost. Other factors such as cost of disruption to building users or the value of contents were given lower rate since the retrofit work of school buildings can be scheduled during vacations. The reference structure represents a wide range of pre-code school buildings which were not designed to effectively resist lateral loads. Columns in this class of non-ductile frame buildings are often weaker than beams, forcing first yielding to be in vertical elements. Buildings with these characteristics exhibit stiffness and strength degradation and large drifts. They are also vulnerable to collapse if shear failure in columns developed. The inelastic analysis results presented hereafter confirm the deficiency in global strength of the reference school building.

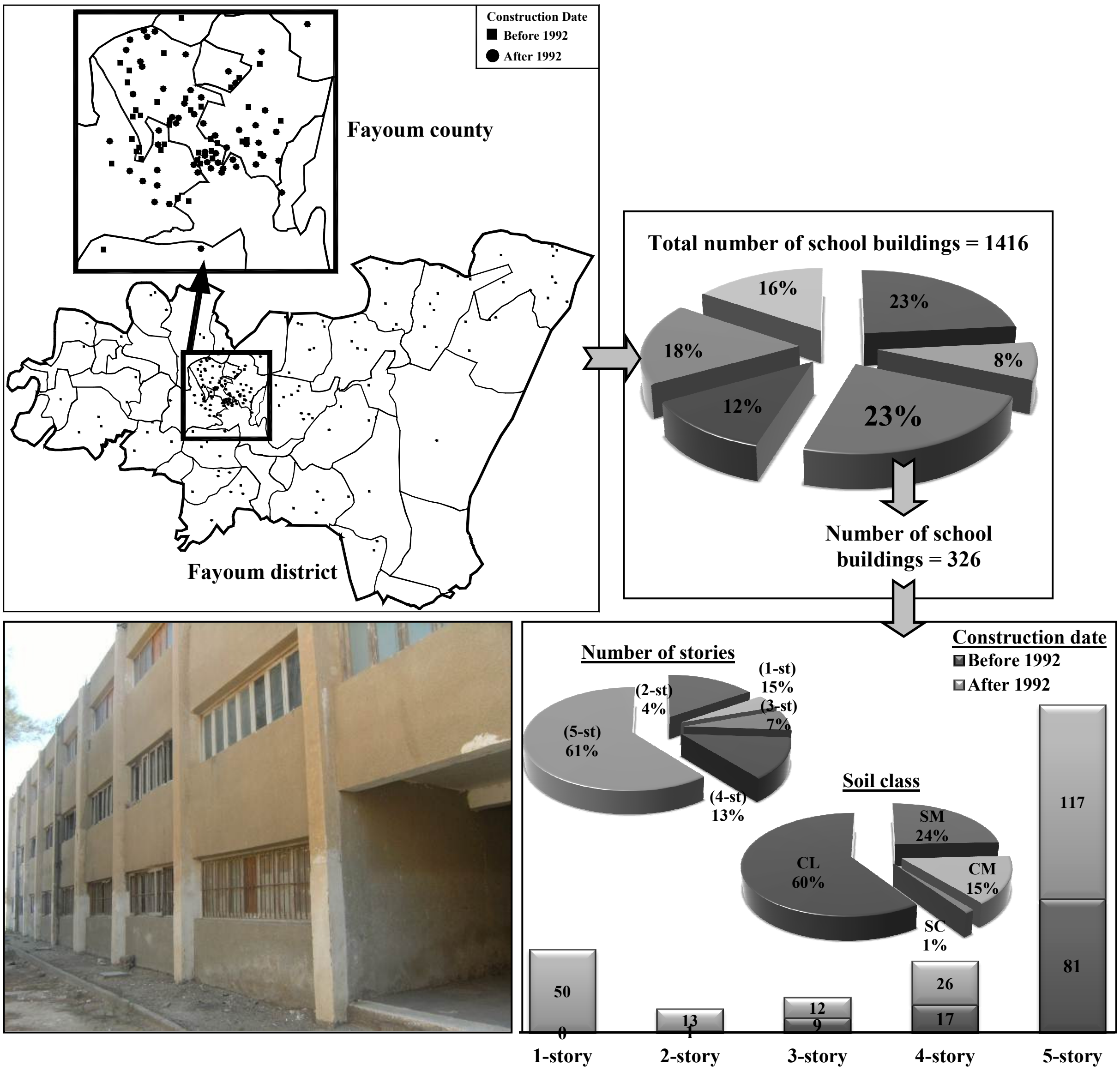

Figure 1. School building inventory of the Fayoum district, Egypt, which includes a construction age map, survey statistics and the selected reference structure

The primary focus of determining a feasible retrofit technique is on vertical members because of their impact in providing both lateral stability and gravity load resistance. Two retrofit techniques applicable to the deficiencies in global strength and stiffness are discussed by FEMA 547 (2006), namely increase in column size and FRP wrap of columns. The former technique is applicable to both strength and stiffness deficiencies as well as the lack of strong column-weak beam detailing, while FRP wrap of columns mainly enhances confinement and shear strength. These two techniques are investigated in the present study with different applications. An efficient retrofit technique is accomplished by enlarging the existing column cross-section with a new RC section. The surface of the existing concrete should be roughened, and drilled dowels between the overlay and existing concrete should be added to achieve composite action. Longitudinal and transverse reinforcing steel is added around the existing column, and concrete jackets are constructed using cast-in-place concrete. The disadvantages of this retrofit approach include the need for formwork and the difficulties in casting and vibrating due to access limitations at the top of the column. This traditional method of enhancing a deficient concrete column increases the column-to-beam strength ratio, and hence enhances the lateral resistance of moment resisting frames. Two alternatives based on this retrofit technique are investigated. RC jackets are applied to all columns in the first alternative, while only ground story columns are strengthened with RC jacketing in the second one to reduce the cost.

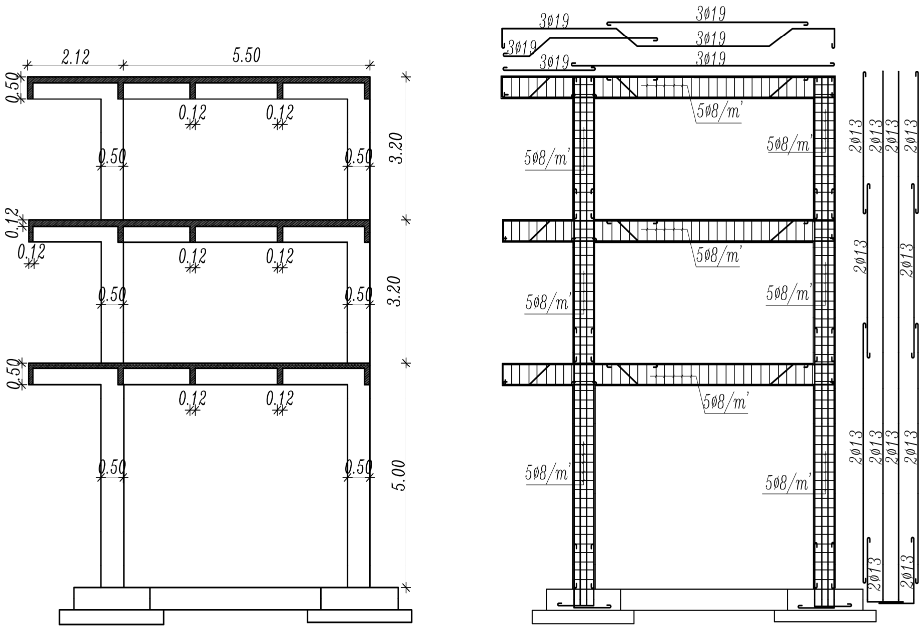

Figure 2. Dimensions and reinforcing steel details of reference structure (B1)

Although FRP overlays are relatively expensive compared to concrete, they can offer advantages when fast construction and minimal disruption are sought. Existing columns are wrapped with unidirectional fibers oriented horizontally. This improves concrete compression behavior and prevents lateral buckling for longitudinal bars. The confinement afforded by this technique increases strength and stiffness of the column, but not to the limit of concrete jacketing. An additional retrofit approach in which the existing column cross-section is overlaid with FRP overlays is investigated in the present study. Three types of FRP material properties are compared, namely low grade (LG), high modulus (HM) and high strength (HS). The material properties shown in Table 1 are selected based on those used in tests of FRP-wrapped specimens. Furthermore, two different thicknesses and two alternative applications for this retrofit technique are investigated in order to evaluate their impact on seismic performance, as shown in Table 1. FRP overlays are applied to all columns in the first alternative, while only ground story columns are retrofitted in the second one to reduce the cost. From the twelve FRP retrofit cases shown in Table 1, two cases are selected based on the ultimate strength obtained from pushover analysis. The lateral strength of selected options, namely B4-HS2 and B5-HS2, are comparable to those obtained using RC jacketing (i.e. B2 and B3), which enables rational comparisons between different retrofit techniques. This paper therefore focuses on the results obtained from the five reference structures, namely B1, B2, B3, B4-HS2 and B5-HS2 in subsequent sections.

Table 1. Description of reference structures, their ultimate lateral strength and material properties

#	Ref	Description/Strengthening technique	Ultimate Strength (kN)	RC/FRP Jacket Thickness (mm)	FRP Elastic modulus (GPa)	FRP Tensile strength (MPa)
1	B1	Pre-code	107.3	N/A	N/A	N/A
2	B2	RC jacketing of all columns	208.9	100	N/A	N/A
3	B3	RC jacketing of ground story columns	174.5	100	N/A	N/A
4	B4-LG1		146.4	1	38.1	580
5	B4-LG2		173.5	2	38.1	580
6	B4-HM1	Wrapping of all columns with FRP	149.5	0.28	629.6	1824
7	B4-HM2	sheets	174.9	0.56	629.6	1824
8	B4-HS1		178.8	0.33	257.0	4519
9	B4-HS2		204.0	0.66	257.0	4519
10	B5-LG1		131.4	1	38.1	580
11	B5-LG2		144.9	2	38.1	580
12	B5-HM1	Wrapping of ground story columns	140.4	0.28	629.6	1824
13	B5-HM2	with FRP sheets	156.3	0.56	629.6	1824
14	B5-HS1		143.0	0.33	257.0	4519
15	B5-HS2		162.0	0.66	257.0	4519

B4-HS2 and B5-HS2 are referred to as B4 and B5, respectively, in subsequent sections.

4. NUMERICAL MODELING

Detailed fiber-based analytical models of the investigated buildings are developed using the verified inelastic analysis platform Zeus-NL, which is capable of predicting the large displacement behavior of space frames under static and dynamic loading (Elnashai et al. 2012). Each structural member is idealized using a number of cubic-elasto-plastic elements capable of representing the spread of inelasticity within the member cross-section and along the member length. The selected sections for modeling of structural members allow the geometric definition of steel, FRP, confined and unconfined concrete regions within the section through the use of the fiber approach. The concrete response is represented using a uniaxial constant confinement concrete model, while a uniaxial trilinear fiber-reinforced plastic model is used to model FRP. An elasto-plastic model is also selected to represent the reinforcing steel (Elnashai et al. 2012). The parameters used in the material models are the actual values rather than nominal material strengths. In addition to the fiber-based numerical models explained above, a refined technique for modeling of the dynamic behavior of large-scale structures, which was termed the improved applied element method (IAEM), is also employed to provide more insights into the failure modes of the reference structures under cyclic loading (Elkholy and Meguro 2005; Elkholy et al. 2010). A multi-layered element has been recently introduced to the IAEM to model non-homogenous cross sections (Elkholy et al. 2012). This element is composed of several layers; each layer has its own material properties. All identical layers in the nearby elements are assumed to be connected to each other by sets of normal and shear springs distributed on the boundary line. These sets of springs represent the microscopic material properties of each layer. The springs connecting the elements enable tracing the gradual spread of inelasticity. A bilinear stress-strain model with kinematic strain hardening is adopted to represent reinforcing steel, while a uniaxial constant confinement concrete model is employed to model the concrete response. This modeling approach also accounts for the geometric nonlinearity under both static and dynamic loading conditions. The efficiency and accuracy of IAEM for predicting the ultimate performance and failure mechanisms of framed structures has been verified elsewhere (e.g Elkholy and Meguro 2005; Elkholy et al. 2012).

5. UNCERTAINTY IN FRAGILITY ANALYSIS

The most important uncertainties in vulnerability analysis are related to: (i) input ground motions, (ii) material properties, (iii) structural characteristics and lateral force resisting system, (iv) modeling approach and analysis method, and (v) performance criteria. Monte Carlo simulations are needed in order to account for the above-mentioned uncertainties, which is very demanding since a large number of inelastic response history analyses are needed. It is therefore more practical to focus on the most important factors that control the fragility. The sensitivity of fragility to major variables was investigated in a number of studies, which concluded that uncertainty in ground motions is more significant than the uncertainties in material and structural properties, particularly when focusing on certain class of structures (Kwon and Elnashai 2006). The present study therefore focuses on the uncertainty in ground motions. Material properties are considered deterministic and equal to mean values. Uncertainties related to analytical modeling and analysis method are also assumed deterministic. The modeling approach (fiber-based) and analysis procedure (IDA) adopted in the present study are the most suitable for deriving vulnerability curves, and significantly contribute in reducing uncertainty compared with other alternatives. Two sets of natural earthquake records are therefore selected for deriving the vulnerability curves of the reference structures, as shown in Figure 3. The selected ground motions represent two seismic scenarios: (i) short-period records, Type I, and (ii) long-period ground motions, Type II. The accelerograms were selected from the Pacific Earthquake Engineering Research Center database (PEER 2012). Ten of the selected natural records represent the short-period seismic scenario, Type I, while the long-period seismic scenario, Type II, is represented by another set of ten ground motions. It is clear from Figure 3 that the mean spectra of the selected records effectively fit the two seismic scenarios recommended by the design code. It is noteworthy that the mean spectra are not less than the design response spectrum for periods ranging from 0.2T to 1.5T, where T is the fundamental period of the structure (ASCE 2010).

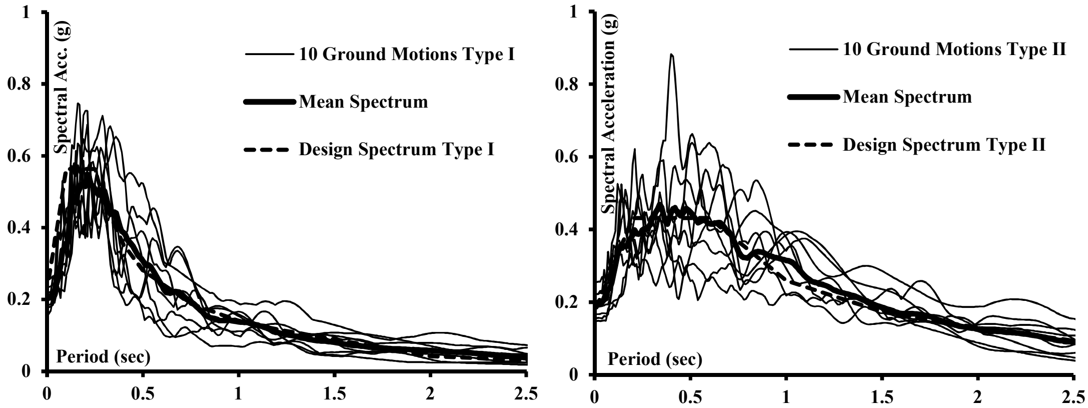

Figure 3. Response spectra of 20 ground motions representing short-period (Type I) and long-period (Type II) earthquakes

6. PERFORMANCE CRITERIA

Interstory Drift (ID) is considered in the present study as the main performance criterion since it is related to the ASCE (2006) performance levels, namely immediate occupancy (IO), life safety (LS), and collapse prevention (CP). A number of approaches are used in the present study to estimate the performance limit states of the pre-code and strengthened buildings and compare them with those proposed by previous studies and design guidelines. Pushover analysis is initially used to define the IO performance level. The lateral capacity envelopes and the first indication of yield in the columns of the reference structures are depicted in Figure 4. The pushover analysis results are also employed to estimate other limit states by monitoring the LS and CP performance limits at the maximum column strength and ultimate confined concrete strain, respectively. The results, which are not presented herein for the sake of brevity, indicate that these limit states occur at an ID ratio of 1.6% and 4.0%, respectively, for the pre-code building. Clearly, these values are higher than those suggested in previous studies. The shear failure is also investigated as a possible failure criterion by employing two shear strength approaches. The first, which is based on experimental results, is capable of representing the reduction of shear supply with the degradation in concrete strength (Priestley et al. 1994). The ACI design code shear strength model is also used after eliminating its safety factors (ACI 2005). The shear models are implemented in a time-step fashion to allow for shear-axial interaction and to account for the instantaneous ductility demand imposed during the analysis (Mwafy and Elnashai 2008). Figure 5 depicts the shear demand-supply response of a ground story column in building B1 from response history analysis using a strong input ground motion scaled to a PGA of 0.5g. This level of PGA causes significant damage for B1 (near collapse). It is clear that shear is not a critical failure criterion for the reference structures since the shear capacity is much higher than demand.

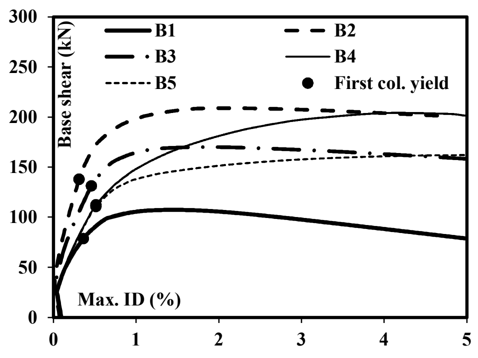

Figure 4. Capacity of reference structures showing the first yield in columns

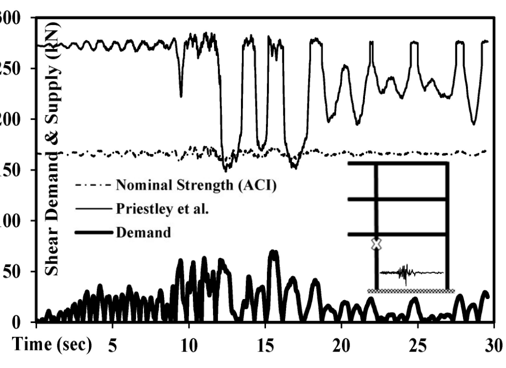

Figure 5. Sample of shear demand-supply response of a ground story column (B1, PGA = 0.5g)

Figure 6 shows a sample of the extensive results obtained from the IAEM analyses for a selected input ground motion. It is clear that the failure modes of building B1 is controlled by the failure at the ground story, which has lower stiffness and strength than other stories due to its height. The IAEM results indicate that the increased strength of columns using RC jackets and FRP wrap has a clear impact on changing the failure modes to be in beams. The ID ratios immediately recorded before collapse are used as the CP limit states of different buildings. These values are summarized in Table 2. Furthermore, incremental dynamic analyses (IDAs) are employed to predict the IO, LS and CP performance levels. A regression analysis for the results obtained from extensive IDAs under the effect of twenty input ground motions are conducted. Figure 7 shows the CP limit states obtained from IDAs using Type II records. The IO and CP performance levels are estimated at yield and collapse, respectively, based on the approach suggested by Vamvatsikos and Cornell (2002). Table 2 summarizes the IDA results at yield and collapse from the regression analysis, while the LS performance level is considered as 50% of the CP level (ASCE 2006). The significant variability of the performance limits under the effect of different ground motions is clear from the results shown in Table 2. The impact of various retrofit approaches also confirms that the reference structures have different performance levels.

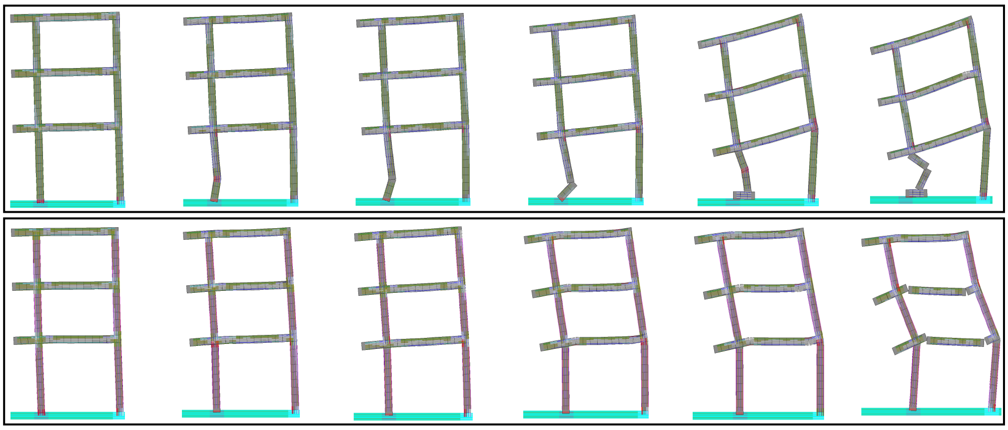

Figure 6. Mapping of collapse mechanisms of B1 (top) and B4 (bottom) using IAEM (selected input ground motion at different time steps)

Table 2: Summary of the performance criteria of reference structures

Limit State			IO					LS					CP				
Reference Structure			B1	B2	B3	B4	B5	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
ASCE (2006)			0.5	1.0				1.0	2.0				2.0	4.0			
Ghobarah et al. (1999)			0.7	0.7				1.1	1.3				2.5	4.8			
Present Study	POA*/ IAEM$^+$		**0.36***	**0.31***	**0.46***	**0.52***	**0.52***	**1.35**	**3.73**	**3.63**	**2.45**	**2.48**	**2.7$^+$**	**7.45$^+$**	**7.25$^+$**	**4.9$^+$**	**4.95$^+$**
	IDA	Max	2.30	1.10	1.20	2.00	1.30	3.85	4.10	5.60	4.05	5.90	7.70	8.20	10.00	8.10	10.00
		Min	0.25	0.40	0.50	0.50	0.60	2.00	2.35	2.05	1.75	2.00	4.00	4.70	4.10	3.50	4.00
		Average	0.81	0.66	0.84	1.23	0.94	2.67	2.88	3.34	3.13	4.49	5.34	5.76	6.56	6.26	8.50
		16%	**0.34**	**0.45**	**0.58**	**0.77**	**0.71**	**2.12**	**2.35**	**2.38**	**2.41**	**3.05**	**4.24**	**4.70**	**4.80**	**4.82**	**6.07**
		50%	0.66	0.62	0.80	1.15	0.91	2.62	2.84	3.21	3.06	4.29	5.23	5.67	6.34	6.12	8.21
		84%	1.27	0.87	1.11	1.72	1.18	3.23	3.42	4.33	3.88	6.02	6.45	6.84	8.37	7.76	11.10
	Adopted Limit States		**0.34**	**0.45**		**0.71**		**1.35**	**2.35**				**2.7**	**4.7**			

POA: Pushover analysis; IAEM: Improved applied element method; IDA: Incremental dynamic analysis

Based on the results summarized in Table 2, it was decided to adopt an ID ratio of 0.34%, 0.45% and 0.71% for the IO performance level of B1, B2-B3, and B4-B5, respectively. These values are obtained from the 16% IDA results, which are more conservative than those proposed by ASCE (2006) and Ghobarah et al. (1999). The adopted CP limit state is 2.7% and 4.7% for pre-code (B1) and retrofitted buildings (B2-B5), respectively. The first value is obtained from the IAEM, which captures the collapse mode at the ground story of building B1. The CP limit states of the retrofitted buildings are obtained from the most conservative 16% IDA results. The CP limit states are generally consistent with the performance limits proposed by Ghobarah et al. (1999). Finally, following the ASCE (2006) approach, the LS limit state is 1.35% and 2.35% for B1 and B2-B5, respectively. It is clear from this discussion that conservative limit states are adopted in the present study based on extensive inelastic simulations and regression analysis of their results. The selected IO, LS and CP limit states are also consistent with previous studies, which lend weight to the results of the present study

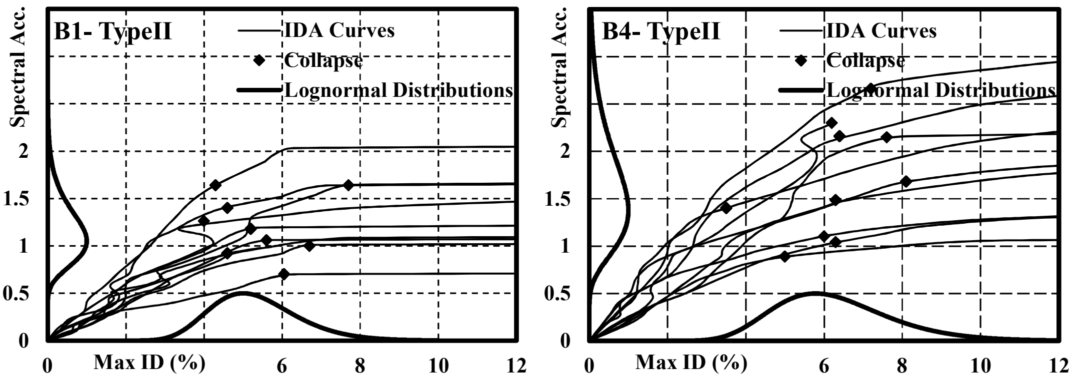

Figure 7. Predicting the CP limit state using IDAs (sample results using Type II records)

7. ASSESSMENT OF RETROFIT TECHNIQUES USING VULNERABILITY FUNCTIONS

Figure 7 shows a sample of the IDA results obtained from ground motions Type II. These earthquake records have more impact on the response of the reference structures due to their high amplifications that cover a wide period range, as shown in Figure 3. A total of 300 points are plotted for each building, where each point represents a PGA-IDR value obtained from an inelastic response history analysis. The statistical distributions obtained from IDAs are used to calculate the probability of exceeding each limit state at different intensity levels (e.g. Wen et al. 2004). It is assumed that the fragility curves can be expressed in the form of two-parameter lognormal distribution functions. Figure 8(a) compares between the fragility curves of the pre-code building (B1) using ground motions Type I and Type II. The differences between the vulnerability relationships obtained from the two seismic scenarios are clear. The slopes are steeper and the probability of exceeding various limit states is much higher under the effect of Type II records compared with Type I ground motions. The results confirm the significant impact of earthquake scenario II, and suggest to focus on this scenario for assessing different retrofit techniques.

Figures 8(b) to (d) compare between the fragility relationship of the pre-code and retrofitted buildings at different limit states. For the sake of brevity, the results are only presented for ground motion Type II due to their higher impact on response compared with Type II, as discussed above. Given the fragility estimates, the seismic vulnerability of reference structures is calculated at the design and twice the design seismic event (i.e. 0.15g and 0.30g, respectively). Figure 9 depicts the limit state probabilities at twice the design earthquake from all seismic scenarios. The probability of exceeding the CP limit state is 43%, and hence significant damage is expected for the pre-code building. This is attributed to the weak column-strong beam behavior of this gravity load designed building. It is also shown from Figure 8(d) that the margin of safety against collapse is unacceptable during moderate-to-severe earthquake intensity levels. The significant increase in the seismic performance of the retrofitted buildings compared with the pre-code counterpart is clear. The retrofit technique using RC jackets is more efficient than the FRP wrap approach. This is attributed to the efficiency of the former technique in controlling lateral deformations since it enhances both strength and stiffness as well as increases the column-to-beam strength ratio (FEMA 2006). This is also shown from the capacity envelopes of the reference structures presented in Figure 4. FRP wrap of columns is less efficient in reducing drift demands since it mainly enhances confinement and shear strength, which do not control the seismic response of the reference structure, as shown from Figure 5. It is also shown that the difference in seismic performance between buildings B2 and B3 is insignificant at twice the design

PGA. The same observation applies to B4 and B5, where the former alternative results in slightly safer performance. School buildings are assigned higher occupancy category than standard buildings, and hence they should experience lower level of damage. The lower probability of damage for the retrofit approach using RC jackets (i.e. B2 and B3) supports selecting it over other alternatives.

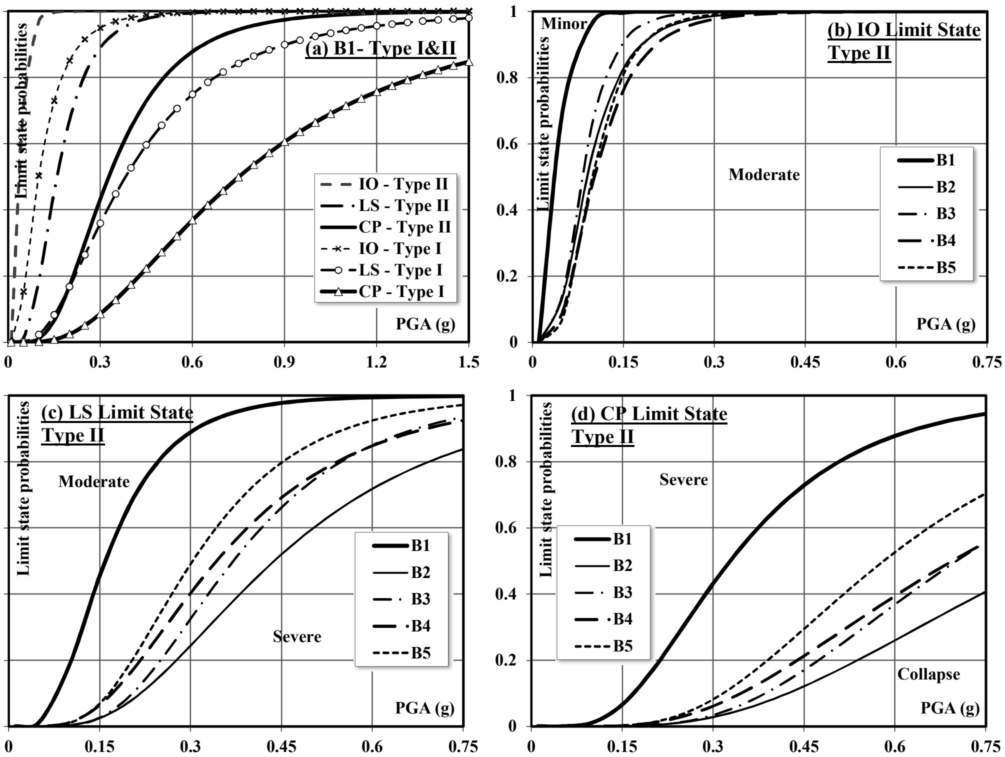

Figure 8. Fragility relationships derived using IDAs

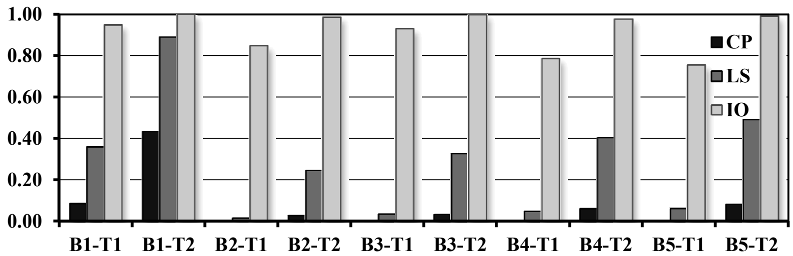

Figure 9. Limit state probabilities at twice the design earthquake for ground motions Type I (T1) & Type II (T2)

8. CONCLUSIONS

The present study was carried out to select an effective retrofit technique for mitigating the seismic risk of the pre-code school building stock in a medium seismicity region, represented by the Fayoum district, Egypt, for the possible application at the urban scale. A field survey of the study area enabled identifying and classifying 1416 school buildings and their construction typologies. A three-story structure was selected to represent typical pre-code school buildings commonly found in medium seismicity urban areas. The existing structural elements of the reference structure were upgraded through the use of two retrofit approaches applicable to the deficiencies in global strength and stiffness, namely RC jackets and FRP wrap of columns. Two additional alternatives for the applications of these retrofit techniques were also investigated. All columns were retrofitted in the first alternative, while only ground story columns were strengthened in the second one to reduce the cost. Three types of FRP material properties and two different thicknesses of FRP overlays were also compared to arrive at the most effective solution. Fifteen different retrofit alternatives were therefore investigated in the present study. Inelastic simulation models were developed using both the fiber modeling approach and the improved applied element method (IAEM) to enable predicting limit states and to provide insights into the failure modes of the reference structures. The ground motion uncertainty was accounted for using 20 natural ground motions, representing two seismic scenarios applicable to the study region. A number of approaches were used to estimate the performance limit states of the pre-code and strengthened buildings. Local response parameters, including member shear response, were monitored and mapped with different performance levels. Conservative performance criteria were selected based on inelastic simulations and the regression analysis of results. The observed damage is described in terms of fragility curves before and after the implementation of mitigation measures. The probability of exceeding various limit states was much higher under the effect of long-period ground motions compared to other earthquake records, which suggests to focus on this scenario for assessment of the retrofit effectiveness. Due to the weak column-strong beam behavior of the pre-code building, the margin of safety against collapse was unacceptable under moderate-to-severe earthquake intensity levels. A significant increase in the seismic performance of the retrofitted buildings compared with the pre-code counterpart was observed. The retrofit technique using RC jackets was more efficient than the FRP wrap approach due to its effectiveness in controlling lateral drift. The lower probability of damage for the retrofit approach using RC jackets supported selecting it over other alternatives, particularly since school buildings are assigned higher occupancy category than standard buildings. The presented sample results from this study illustrated the significance of assessing different retrofit alternatives using reliable seismic evaluation procedures to arrive at an effective mitigation strategy. The results also confirm the pressing need for expanding this study to cover other classes of structures in the study region.

AKCNOWLEDGEMENT
This work was partially supported by the United Arab Emirates University under research grant RSA-1108-00163.

REFERENCES

ACI (2005). *Building Code Requirements for Structural Concrete and Commentary (318-05)*, American Concrete Institute, Detroit, Michigan

ASCE (2006). *Seismic rehabilitation of existing buildings, ASCE Standard ASCE/SEI 41-06 "formerly FEMA 356"*, American Society of Civil Engineers, Reston VA

ASCE (2010). *Minimum design loads for buildings and other structures, ASCE Standard ASCE/SEI 7-10*, American Society of Civil Engineers, Reston, VA

Elkholy, S., Gomaa, M. and Akl, A.A. (2010). Collapse analysis of R/C structures using improved applied element method. *9th Int. Symp. on New Technologies for Urban Safety of Mega Cities in Asia, Kobe, Japan*.

Elkholy, S., Gomaa, M. and Akl, A.A. (2012). Improved applied element simulation of RC and composite structures under extreme loading conditions. *Arabian Journal for Science and Engineering* **In press**.

Elkholy, S. and Meguro, K. (2005). Numerical study of collapse behavior of steel buildings due to extremely high seismic load. *Journal of Earthquake Engineering* **28**, 1-8.

Elnashai, A.S., Papanikolaou, V. and Lee, D. (2012). *Zeus-NL - A System for Inelastic Analysis of Structures - User Manual,* , Mid-America Earthquake Center, Univ. of Illinois at Urbana-Champaign, Urbana, IL

FEMA (2006). *Techniques for the Seismic Rehabilitation of Existing Buildings, FEMA 547*, Federal Emergency Management Agency, Washington, D.C

Ghobarah, A., Abou-Elfath, H. and Biddah, A. (1999). Response-based damage assessment of structures. *Earthquake Engineering & Structural Dynamics* **28: 1**, 79-104.

Kwon, O.S. and Elnashai, A.S. (2006). The effect of material and ground motion uncertainty on the seismic vulnerability curves of RC structure. *Engineering Structures* **28: 2**, 289-303.

Mwafy, A.M. and Elnashai, A.M. (2008). Importance of shear assessment of concrete structures detailed to different capacity design requirements. *Engineering Structures* **30: 6**, 1590-1604.

PEER (2012). *PEER NGA database*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, California

Priestley, M.J.N., Verma, R. and Xiao, Y. (1994). Seismic shear strength of reinforced concrete columns. *Journal of Structural Engineering* **120: 8**, 2310-2329.

Vamvatsikos, D. and Cornell, C.A. (2002). Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics* **31: 3**, 491-514.

Wen, Y.K., Ellingwood, B.R. and Bracci, J. (2004). *Vulnerability function framework for consequence-based engineering*, University of Illinois at Urbana-Champaign, Urbana