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ROOF LATERAL DISPLACEMENT FOR GRAVITY LOAD DESIGNED RC FRAMES SUBJECTED TO EARTHQUAKES

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ABSTRACT

The roof lateral displacement for RC frames is very significant parameter in performance based engineering and should be within acceptable limits as per the requirement of different performance levels. Data obtained from the time history dynamic analysis for a series of gravity load designed (GLD) RC frame was used as input data in a statistical program called SPSS 16.0, and a statistical analysis was done and a power equations was proposed to estimate the roof lateral displacement for the GLD RC frames. Three equations were proposed for estimating the roof lateral displacement. The first one is for the bare frame models, the second is for infilled frame models and the third is for infilled frame with open ground story. The equations for estimating the roof lateral displacement for GLD frames with different type of infill (bare, infilled and open ground story models) are proved to be acceptable accuracy and they can be used to estimate the roof lateral displacement for GLD RC frames if they meet the conditions set out.

Keywords: gravity load designed, SPSS 16.0, frame models.

1. Introduction

Reinforced concrete (RC) framed structures are very common in many countries in the world, especially in developing countries, and are the predominant structural system in Arab Countries. In various parts of the world, especially in Arab World, reinforced concrete structures even in seismic zones have been designed only for gravity load. Such structures though performing well under conventional gravity load case, could lead to questionable structural performance under earthquake. In most cases, those structures are vulnerable to any major earthquake and so these structures need immediate assessment to avoid a collapse which brings a huge loss of human lives and economy that the world has witnessed for several times.

Masonry infill walls are frequently used as interior partitions and exterior wall in RC frames. Usually, the infill walls are treated as non-structural element and their influences on the structural response are generally ignored. Many RC buildings constructed in recent

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times have a special feature, the ground story is left open for the purpose of parking (Fig.1), i.e., columns in the ground story do not have any partition walls (of either masonry or RC) between them. Such buildings are often called open ground story buildings. These buildings look as if they are supported by chopsticks! Open ground story buildings have consistently shown poor performance during past earthquakes across the world [1].

Recent earthquakes have clearly shown that the damages done to the buildings with infill were considerable less than those without infill and the difference was quite a bit significant. Therefore, the structural contribution of infill walls cannot simply be neglected particularly in regions of moderate and high seismicity where, the frame–infill interaction may cause substantial increase in both stiffness and strength of the frame. In fact, the interaction between the infill and the frame has a dual effect: it may or may not improve the seismic performance of the structure due to several reasons such as regular distribution and continuity of infill.

Fig. 1. Typical example of open ground story building[1]

Earthquakes are one of nature's greatest hazards to life on this planet. The impact of this phenomenon is sudden with little or no warning to make preparations against damages and collapse of buildings/structures. Recent earthquakes across the world, including the 1982 Dhamar earthquake in Yemen, the 1992 Cairo earthquake in Egypt, the 1995 Hyogo-ken Nanbu earthquake in Japan, the 1999 Izmit and Ducze earthquakes in Turkey, the 2001 Bhuj earthquake in India, the 2001 Chi Chi earthquake in Taiwan, the 2003 Boumerdes earthquake in Algeria, the 2009 Southern Sumatra in Indonesia, and the 2011 Van earthquake in Turkey revealed major seismic deficiencies in the RC buildings, some of which led to catastrophic collapses causing a death toll measured in thousands. One of the major causes of seismic vulnerability associated with these buildings is that, in the developing countries, a large number of the existing RC frame buildings have been designed to resist only vertical loads and had insufficient lateral resistance and the architects and engineers were without formal training in the seismic design and construction and have been built by inadequately skilled construction workers [1 - 6].

In the recent years, special attention has been given to the investigation on the seismic behavior of reinforced concrete buildings designed for gravity load only. Most of these structures have been typically designed and built before the introduction of adequate seismic design code provisions. In the Arab World, until late 1990s, there was no regulation to design and construct building structures for seismic resistance and most building structures were designed to resist gravity loads only (GLD), for example, in Egypt the first official code of practice to consider seismic loading was published by the Ministry of Housing in 1989 [3], and in Syria the seismic design for buildings was mandatory as a law in1997 [7].Whereas, unfortunately, no building seismic codes are available for the Arabian Peninsula states [8] and Yemen [2].

Because there is a large inventory of buildings that were designed and constructed without considering the seismic loads, it is believed that many of these structures may pose an unacceptable life-safety hazard in the event of a major earthquake. Also non ductile detailing practice employed in these structures makes them prone to potential damage and failure during earthquake. This fact explains the basic need for identification of such buildings, the evaluation of their expected seismic performance, and if needed, their seismic strengthening.

The roof lateral displacement is very significant parameter in performance based engineering and should be within acceptable limits as per the requirement of different performance levels. Hence in this study, a focus is given to propose an expression for estimating the roof lateral displacement for RC frames designed for gravity load only (GLD) by using and analyzing the results obtained in a previous study [9] done by the authors for a series of GLD RC with different number of bays, different number of stories, different bay spanned three types of presences of infill (bare frame "BF", infilled frame "IN" and infilled frame with open ground story "OG"). The data will be analyzed using a statistical program called SPSS 16.0 in order to propose an expression to estimate the roof lateral displacement for three types of GLD RC; bare frame, infilled frame and infilled frame with open ground story.

2. General description of SPSS 16.0 software

The abbreviation SPSS16.0 stands for Statistics Package for the Social Sciences and is considered as one of the leading statistical software applications and it is probably the most popular general statistics packages in academia. The integration of the graphics module to the Base with excellent interface is just one example of the state of the art of the product[10].

SPSS is a Windows based program that can be used to perform data entry and analysis and to create tables and graphs. SPSS has scores of statistical and mathematical functions, scores statistical procedures, and a very flexible data handling capability. Some of the functionalities of SPSS are: Descriptive Statistics, Reliability tests, Correlation, T-tests, Regression and curve estimation.

The Curve Estimation procedure produces curve estimation regression statistics and related plots for 11 different curve estimation regression models. A separate model is produced for each dependent variable. You can also save predicted values, residuals, and prediction intervals as new variables. The curve estimation regression models are linear, logarithmic, inverse, quadratic, cubic, power, compound, S-curve, logistic, growth, and exponential.

3. General description of models under study

In our previous study [9], time history analysis was performed to study the effect of selected parameters in the behavior of reinforced concrete frames under earthquake loads. A series of multistory RC frames were designed for gravity loads only (1.4D.L+1.7L.L) without considering the seismic loads as typically found in most seismic prone countries before the introduction of adequate seismic design code provisions. All frame models have a constant 3m story height except the ground story is 4m (Fig.2). The parameters considered for each RC frame model under study are: number of stories ("n_1"= 2, 4, 6, 8, 12 and 16 stories), number of bays ("n_2" = 1, 2, 3, and 4 bays) and the bay span ("L" = 4, 6, and 8m) and three types of infill wall presence (without infill “BF”, full infill "IN" and full infill with open ground story "OG") Fig.3. The detailing for the structure was in accordance with the general non-seismic provisions of the ACI 318-89 Code [11]. for more details see references [9] and [12]

It should be noted here that for differentiating between each models, a Model_ID was given for all models to describe the model's number of stories, number and span of bays and the type of infill. The Model_ID is composed of three parts, the first part consists of number followed by the letter "S" expresses the number of stories and the second part consists of letter "B" preceded by a number that represents the number of bays, where the number that follows the letter "B" represents the bay length, while the third part indicates the existence of masonry infill or not ("BF": without infill, "IN": full infill in all stories and "OG": open ground story and with infill in all others stories). For example, the ID (4S_3B6_BF) stands for model with four stories, three bays with six meter span and type of frame is bare frame.

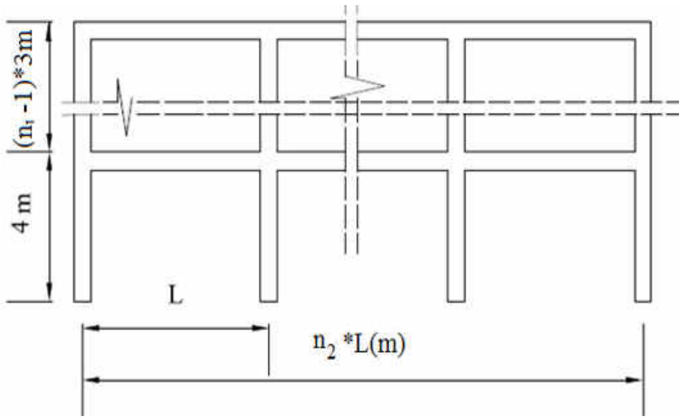
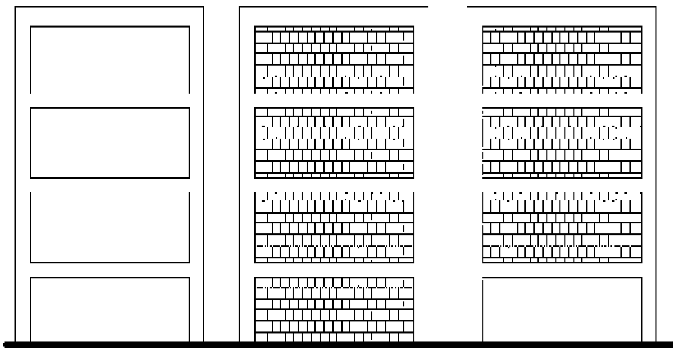


Fig. 2. RC frame models under study, where "n_1" is the number of stories, "n_2" is the number of bays and "L" is the bay span.



a) Bare Frame “BF” b) Full Infill “IN” c) Open Ground Story “OG”

Fig. 3. General Types of RC Frame under study according to presence of infill

4. Data Input and statistical analysis

The roof lateral displacements obtained from the time history dynamic analysis for models under study were listed in Table 1.

Table 1.
Roof lateral displacement for all models under study [9]

Number of Stories	Number of Bays and Frame Type											
	One-Bay			Two-Bay			Three-Bay			Four-Bay		
	BF	IN	OG	BF	IN	OG	BF	IN	OG	BF	IN	OG
2	10.03	2.07	12.25	9.06	1.75	10.19	8.64	1.56	9.14	8.22	1.46	8.84
4	17.49	9.82	14.83	15.49	9.46	12.42	14.44	8.47	11.82	13.61	8.04	11.40
6	27.84	18.18	16.28	23.30	16.98	15.63	20.80	16.26	15.54	18.89	16.05	15.39
8	55.15	38.20	41.37	48.61	27.57	30.22	41.82	22.84	26.39	38.57	20.01	22.39
12	74.26	61.00	63.71	68.23	52.20	55.30	64.06	48.19	52.70	58.88	45.60	45.65
16	108.3	91.09	78.73	94.76	78.89	61.33	84.82	70.95	48.80	78.94	65.26	51.73

The data obtained from the analysis was used as input data in a statistical program called SPSS, and a statistical analysis was done, using the power curve estimation regression model, in order to propose a curve and equation to estimate the roof lateral displacement for the GLD RC frames subjected to earthquake. The estimation was done under the following condition:

- The reinforced concrete frame is designed for gravity load only without considering the seismic loads (no lateral loads were considered for the design).
- The specified strengths of the concrete and reinforcing steel are, respectively, f_c =21 MPa and f_y = 400 MPa.
- The earthquake time history acceleration is the N-S EL-Centro 1940 with peak ground acceleration 0.31g.
- The masonry infill used is brick units with 100mm width.

As discussed in previous study, it can be said that the roof lateral displacement is dependent on different parameters as follows:

- There is a positive correlation between the roof lateral displacement and the total height of the frame ($RLD \alpha H_t$).
- There is an inverse correlation between the roof lateral displacement and the total width of the frame ($RLD\ \alpha\ \frac{1}{L_t}, \frac{1}{n_2}$).
- There is a positive correlation between the roof lateral displacement and the total dead loads for the frame ($RLD\ \alpha\ DL_t$).
- There is an inverse correlation between the roof lateral displacement and the total area of column sections at the base ($RLD\alpha\ \frac{1}{A_{ct}}$).

In order to propose a curve and equation to estimate the roof lateral displacement for the GLD RC frames and with taking the effect of different parameters a parameter called “X” is assumed to involve the effect of the parameters under study as follow:

$$X = \sqrt{\frac{1}{n_2} \cdot \frac{H_t}{L_t} \cdot \frac{1}{\sum A_c}} * DL_t \quad (1)$$

Where: H_t is the total frame height in (m); $n_2$is the number of bays; $L_t$is the total frame width in (m); $\sum A_c$ is summation of columns section area at the base in(m^2), and DL_t is the total dead load (KN) applied on the frame.

The parameter "X" was calculated for all models under study and used with roof lateral displacement obtained as input data to the statistical program and a regression analysis was done to draw a curve of best fit through the data points for the models. These processes were done for the three cases of infill (Bare frame "BF", infilled frame "IN" and open ground story "OG" models). After drawing the curve of best fit the equation has been derived, it can be used to predict the change in roof lateral displacement "*RLD*" for any change in X. It can therefore be used to extrapolate between the existing data points as well as predict results which have not been previously observed.

4. Results and discussions

4.1. Estimating the roof lateral displacement for Bare Frame models

For the bare frame models the curve of best fit for estimating the roof lateral displacement is shown in Fig.4. The corresponding correlation coefficient (R^2) was observed = 0.954, and the equation is derived as power equation:

$$RLD_{BF} = 0.12034 * \left(\sqrt{\frac{1}{n_2} \cdot \frac{H_t}{L_t} \cdot \frac{1}{\sum A_c}} * DL_t\right)^{0.8375}$$

$$RLD_{BF} = 0.12034 * (X)^{0.8375} \quad (2)$$

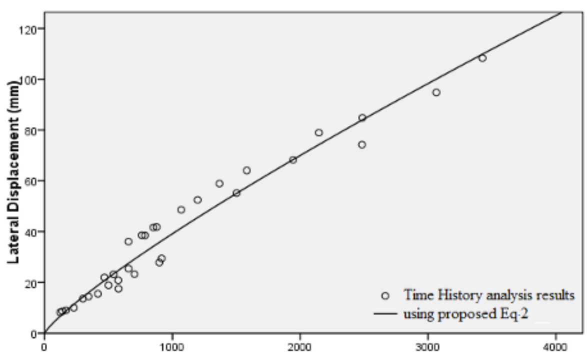


Fig. 4. Estimating the RLD for bare frame models.

Fig.5 and Table 2showthe correlation of estimated value by (Eq.2) with the obtained values, a comparison between the estimated and observed roof lateral displacement for bare frame models. It is observed that the equation (Eq.2)estimates the values quite accurately and not too far away from the analytical results and this proves the validity of the model. The slope of the trendline between the observed and estimated results was 0.984 (θ=44.54°, θ is the angel between the trendline and the horizontal axis).

Table 2.
Estimating RLD for bare frame models

Model ID	X	RLD (Time History analysis)	RLD (Proposed Eq.2)	Error
2S_1B8_BF	228.20	10.02	11.36	-1.34
2S_2B8_BF	167.79	9.06	8.78	0.28
2S_3B8_BF	139.29	8.64	7.51	1.13
2S_4B8_BF	121.72	8.22	6.71	1.51
4S_1B8_BF	577.66	17.49	24.73	-7.24
4S_2B8_BF	417.49	15.49	18.85	-3.36
4S_3B8_BF	343.95	14.44	16.02	-1.58
4S_4B8_BF	299.32	13.61	14.26	-0.65
6S_1B4_BF	1197.40	52.49	45.54	6.95
6S_2B4_BF	851.11	41.67	34.22	7.45
6S_3B4_BF	785.71	38.52	32.00	6.52
6S_4B4_BF	656.02	36.08	27.52	8.56
6S_1B6_BF	915.20	29.46	36.36	-6.90
6S_2B6_BF	656.10	25.45	27.52	-2.07
6S_3B6_BF	538.97	23.16	23.34	-0.18
6S_4B6_BF	468.34	21.96	20.75	1.21
6S_1B8_BF	898.05	27.84	35.79	-7.95
6S_2B8_BF	702.87	23.26	29.15	-5.89
6S_3B8_BF	576.03	20.83	24.68	-3.85
6S_4B8_BF	499.99	18.89	21.92	-3.03
8S_1B8_BF	1501.61	55.15	55.05	0.10
8S_2B8_BF	1068.75	48.61	41.41	7.20
8S_3B8_BF	876.05	41.82	35.06	6.76
8S_4B8_BF	760.47	38.57	31.14	7.43
12S_1B8_BF	2482.86	74.26	83.88	-9.62
12S_2B8_BF	1944.15	68.23	68.35	-0.12
12S_3B8_BF	1582.11	64.06	57.51	6.55
12S_4B8_BF	1368.10	58.88	50.92	7.96
16S_1B8_BF	3425.39	108.34	109.83	-1.49
16S_2B8_BF	3064.60	94.76	100.05	-5.29
16S_3B8_BF	2485.75	84.82	83.96	0.86
16S_4B8_BF	2145.82	78.94	74.24	4.70
			Standard deviation	**5.28**

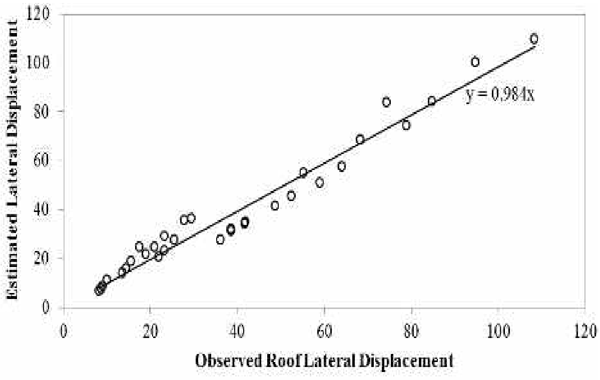


Fig. 5. Relation between Time History Analysis Result and Estimated Roof Lateral Displacement for Bare Frame models

4.2. Estimating the roof lateral displacement for Infilled Frame models

For the Infilled frame models the curve of best fit for estimating the roof lateral displacement is shown in Fig.6 with (R^2 = 0.957) and the equation is derived as power equation :

$$RLD_{IN} = 0.003645 * \left(\sqrt{\frac{1}{n_2}.\frac{H_t}{L_t}.\frac{1}{\sum A_c}} * DL_t\right)^{1.272}$$

$$RLD_{IN} = 0.003645 * (X)^{1.272} \qquad (3)$$

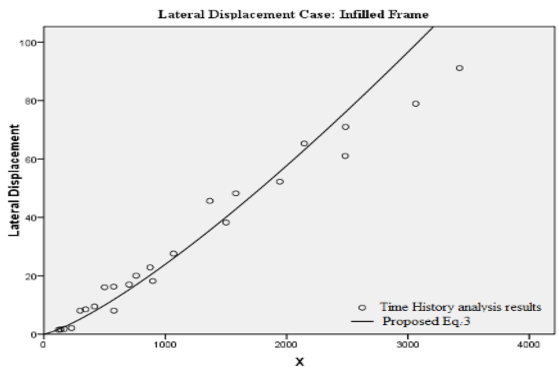


Fig.6. Estimating the RLD for infilled frame models.

Fig.7 and Table 3shows the correlation of estimated value by (Eq.3) with the obtained values, a comparison between the estimated and observed roof lateral displacement for infilled frame models. It is observed that the equation (Eq.3) estimates the values quite accurately and not too far away from the analytical results and this proves the validity of the model. The slope of the trendline between the observed and estimated results was 1.10 (θ=47.7°).

4.3. Estimating the roof lateral displacement for Open Ground Story Frame models

For the open ground story models the curve of best fit for estimating the roof lateral displacement is shown in Fig.8 with (R^2 = 0.904) and the equation is derived as power equation :

$$RLD_{OG} = 0.30045 * \left(\sqrt{\frac{1}{n_2} \cdot \frac{H_t}{L_t} \cdot \frac{1}{\sum A_c}} * DL_t \right)^{0.65256}$$

$$RLD_{OG} = 0.30045 * (\,X)^{0.65256} \qquad (4)$$

Fig.9 and Table 4 illustrates a comparison between the estimated and observed lateral displacement for open ground story models. It shows that the estimation equation gives an acceptable accuracy. The slope of the trendline between the observed and estimated results was 0.951 (θ=43.56°).

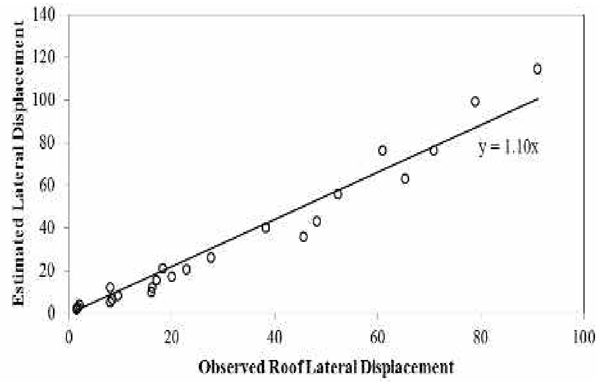


Fig.7. Relation between Time History Analysis Result and Estimated RLD for infilled frame models

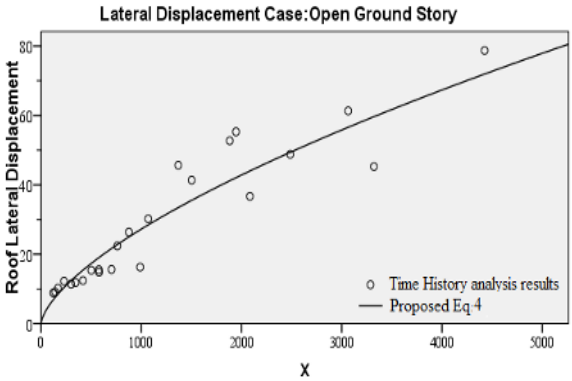


Fig. 8. Estimating the RLD for open ground story models.

Table 3.
Estimating RLD of Infilled frame models

Model ID	X	RLD (Time History analysis)	RLD (Proposed Eq.3)	Error
2S_1B8_IN	228.20	2.07	3.64	-1.57
2S_2B8_IN	167.79	1.75	2.46	-0.71
2S_3B8_IN	139.29	1.56	1.94	-0.38
2S_4B8_IN	121.72	1.46	1.64	-0.18
4S_1B8_IN	577.66	8.04	11.88	-3.84
4S_2B8_IN	417.49	9.46	7.86	1.60
4S_3B8_IN	343.95	8.47	6.14	2.33
4S_4B8_IN	299.32	8.04	5.15	2.89
6S_1B8_IN	898.05	18.18	20.82	-2.64
6S_2B8_IN	702.87	16.98	15.24	1.74
6S_3B8_IN	576.03	16.26	11.83	4.43
6S_4B8_IN	499.99	16.05	9.88	6.17
8S_1B8_IN	1501.61	38.2	40.03	-1.83
8S_2B8_IN	1068.75	27.57	25.98	1.59
8S_3B8_IN	876.05	22.84	20.17	2.67
8S_4B8_IN	760.47	20.01	16.85	3.16
12S_1B8_IN	2482.86	61	75.90	-14.90
12S_2B8_IN	1944.15	52.2	55.60	-3.40
12S_3B8_IN	1582.11	48.19	42.78	5.41
12S_4B8_IN	1368.10	45.6	35.56	10.04
16S_1B8_IN	3425.39	91.09	114.29	-23.20
16S_2B8_IN	3064.60	78.89	99.20	-20.31
16S_3B8_IN	2485.75	70.95	76.01	-5.06
16S_4B8_IN	2145.82	65.26	63.04	2.22
			Standard deviation	**5.86**

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Table 4.
Estimating RLD of open ground story models

Model ID	X	RLD (Time History analysis)	RLD (Proposed Eq.4)	Error
2S_1B8_OG	228.20	12.25	10.39	1.86
2S_2B8_OG	167.79	10.19	8.50	1.69
2S_3B8_OG	139.29	9.14	7.53	1.61
2S_4B8_OG	121.72	8.84	6.90	1.94
4S_1B8_OG	577.66	14.83	19.05	-4.22
4S_2B8_OG	417.49	12.42	15.41	-2.99
4S_3B8_OG	343.95	11.82	13.58	-1.76
4S_4B8_OG	299.32	11.4	12.41	-1.01
6S_1B8_OG	988.05	16.28	27.04	-10.76
6S_2B8_OG	702.87	15.63	21.65	-6.02
6S_3B8_OG	576.03	15.54	19.02	-3.48
6S_4B8_OG	499.99	15.39	17.34	-1.95
8S_1B8_OG	1501.61	41.37	35.54	5.83
8S_2B8_OG	1068.75	30.22	28.46	1.76
8S_3B8_OG	876.05	26.39	25.00	1.39
8S_4B8_OG	760.47	22.39	22.80	-0.41
12S_1B8_OG	2082.86	36.71	44.00	-7.29
12S_2B8_OG	1944.15	55.3	42.06	13.24
12S_3B8_OG	1882.11	52.7	41.18	11.52
12S_4B8_OG	1368.10	45.65	33.44	12.21
16S_1B8_OG	4425.39	78.73	71.94	6.79
16S_2B8_OG	3064.60	61.33	56.60	4.73
16S_3B8_OG	2485.75	48.8	49.38	-0.58
16S_4B8_OG	2145.82	51.7	44.90	6.8
			Standard deviation	**6.02**

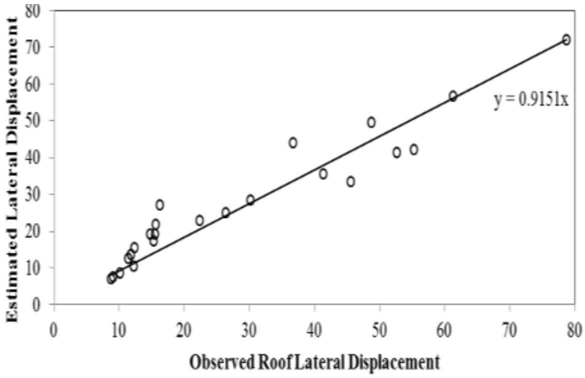

Fig. 9. Relation between Time History Analysis Result and Estimated RLD for open ground story models

5. Conclusion

The data obtained from the time history dynamic analysis for a series of GLD RC frame was used as input data in a statistical program called SPSS, and a statistical analysis was done and a power equations was proposed to estimate the roof lateral displacement for the GLD RC frames. Three equations were proposed for estimating the roof lateral displacement, the first one is for the bare frame models, the second is for infilled frame models and the third is for infilled frame with open ground story. It was observed that the equations proposed estimates the values quite accurately and not too far away from the analytical results and this proves the validity of the model. The slope of the trendline between the observed and estimated results for the three equations was 0.984 (θ=44.54^o), 1.10 (θ=47.7^o) and 0.951 (θ=43.56^o).

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الازاحة الافقية عند السطح للاطارات الخرسانية المسلحة المصممة لتحمل القوى العمودية فقط والمعرضة لقوى الزلازل

الملخص العربى

تعتبر الازاحة الافقية عند السطح للإطارات الخرسانية المسلحة من اهم العوامل لتقييم أداء وكفاءة المباني هندسيا و يجب أن تكون ضمن حدود مقبولة وفقا لمتطلبات مستويات الأداء المختلفة. تم استخدام قيم الازاحات الجانبية التي حصلنا عليها من تحليل ديناميكي لسلسلة من الاطارات الخرسانية المسلحة المصممة لتحمل القوى الرأسية فقط (GLD) والمعرضة لاحمال الزلازل كبيانات ادخال في البرنامج الاحصائي SPSS، و أجري التحليل الإحصائي للبيانات وتم اقتراح معادلات لتقدير الازاحات الأفقية المتوقعة للاطارات الخرسانية المسلحة والمصممة لتحمل القوى الرأسية فقط. تم اقتراح ثلاث معادلات لثلاثة انواع من الاطارات الخرسانية المسلحة، المعادلة الاولى تم اقتراحها للاطارات الخرسانية المسلحة العارية او التي تركت الفراغات بين الاعمدة فيها بدون حوائط بناء (Bare Frame)، والمعادلة الثانية للاطارات الخرسانية المسلحة بافتراض ان جميع الفراغات بين الاعمدة مليئة بحوائط البناء في جميع ادوارها (Infilled Frame)، اما المعادلة الثالثة فكانت للاطارات الخرسانية المسلحة المليئة بحوائط البناء في جميع ادوارها ماعدا الدور الارضي الذي ترك بدون حوائط لاستخدامه كحالات خاصة مثل مواقف السيارات (Open Ground Story Frame). وجد ان المعادلات المقترحة اعطت دقة مقبولة لتوقع الازاحات الجانبية عند السطح للاطارات الخرسانية المسلحة المستوفية للشروط المحددة لاستخدام هذه المعادلات، وننصح باستخدامها في الحالات المماثلة.