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Influence of green roofs on the seismic response of frame structures

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Abstract. Environmental and operational benefits of green roofs are manifolds; however, their main disadvantages are cost and weight. New technology enabled the use of plastics to reduce the weight of green roof systems to promote their installation. To maximize their potential benefits, green roofs can be installed on existing structures. This study evaluates the influence of green roofs on the seismic response of 3, 6, and 8 storey reinforced concrete ductile moment resisting frames, which were designed according to current seismic standards, however, not designed for green roofs. For each frame, three different types of roofs are considered: gravel flat roof, extensive green roof, and intensive green roof. Nonlinear dynamic time history analysis using an ensemble of twenty real earthquake records was performed to determine the inter-storey drift demand and roof drift demand for each frame. Eigenvalue analysis was also performed to determine the impact of green roofs weight on the elastic and cracked periods of the structure. Results from the analysis demonstrated that intensive and extensive green roofs do not affect the seismic performance of reinforced concrete frame structures.

Keywords: green roofs; RC frames; dynamic time history analysis; seismic response; base shear; drift

1. Introduction

Green roof is a sustainable application that partially replaces the natural landscape destroyed due to the construction of buildings. Growing vegetation on rooftops has been developed as an option to address well-known environmental issues such as: global warming or air pollution (Bianchini and Hewage 2012). Environmental benefits during green roofs lifespan can be listed as follows: reduction of energy demand for heating and cooling, mitigation of urban heat island, reduction and delay of storm water runoff, improvement in air quality, replacement of displaced landscape, enhancement of biodiversity, provision of recreational and agricultural spaces, and insulation of a building for sound (Clark *et al*. 2008, Czemiel 2010, Molineux *et al*. 2009,

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Santamouris *et al*. 2007, Yang *et al.* 2008).

Green roofs are also known as vegetative roofs due to the growth of vegetation in their surface. Moreover, green roofs can be classified by their characteristics and vegetation type in two major categories: intensive roofs and extensive roofs (Molineux *et al.* 2009, Xeroflor 2011). Intensive roofs need a reasonable depth of soil and are usually associated with roof gardens (Molineux *et al.* 2009, Snodgrass and McIntyre 2010). Extensive roofs have a relatively thin layer of soil, grow sedums and moss and are designed to be virtually self-sustaining and require minimum maintenance (Molineux *et al.* 2009).

Popularity of green roofs is increasing due to their environmental benefits; nevertheless, their cost disadvantage has been a challenge to the industry (Nelms *et al.* 2007). Depending on the type of green roof, additional weight can be added to the roof, which may lead to changes in the structural design that can result in a more expensive structure (Clark *et al.* 2008). There is no available/published literature that depicts the performance of existing buildings by incorporating green roofs. Therefore, this paper evaluates the effects of green roofs on the seismic performance of existing frame buildings.

The demand of using green roofs in new buildings is increasing (City of Portland 2008); however, to maximize their positive effects on urban settings, green roofs need be installed on existing structures. Installing vegetative roofs on existing structures lead to another challenge where it might be critical to determine their influence on the seismic response of the structure in a seismic risk zone. Additionally, if required, it might be important to determine proper retrofitting methods and their relevant costs.

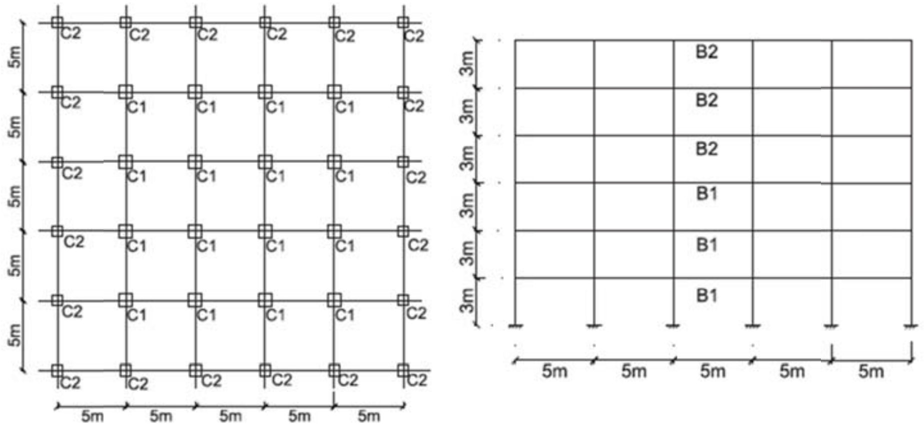
The seismic retrofit strategy for an existing reinforced concrete (RC) frame may include partial demolition and/or mass reduction, addition of new lateral load resistance system, member replacement, and transformation of non-structural into structural components to enhance the overall seismic performance of the frame by increasing lateral strength, reducing drift and/or increasing ductility (Snodgrass and McIntyre 2010, Niroomandi *et al.* 2010). The retrofitting method should be an applicable, effective, and economic solution; therefore, the selection process is a complex procedure. Thus, selecting, designing and applying the best retrofit solution is merely based on engineering judgment (Baros and Dristos 2008).

To have a comparative analysis in this paper, 3 regular reinforced concrete (RC) buildings of different storeys, designed according to current seismic standards, have been considered as per Alam *et al.* (2012). These buildings were not designed to support green roof on the top. Here, green roof was applied in each building with three different types; thus, nine RC frame buildings were analyzed. This paper attempts to illustrate that without much modification or retrofitting, green roofs can be potentially installed in existing frame buildings, if they are designed according to current seismic standards.

2. Properties and modeling of the structures

The typical plan and elevation of the steel RC buildings are shown in Figs. 1(a)-(b). The structures were analyzed as per National Building Code of Canada (NBCC 2005) and designed as moderately ductile moment resisting frames based on equivalent static force procedure according to Canadian Standards Association A23.3-04 (CSA 2004). For concrete the following material properties are chosen: the strain at peak stress is 0.2%, the compressive strength ($f'c$) is 35 MPa, and the tensile strength is 3.5 MPa. Steel was modeled with a modulus of elasticity (E) of 2×10^5

MPa and yield strength (*fy*) of 400 MPa, while the strain hardening parameter was considered as 0.5%. For further details of the building design process and dimensions of each element the reader is referred to Alam *et al*. (2012).



(a) (b)

Storey Id	Floor level	Description	Column ID	
			C1	C2
3 Storey building	Up to roof	Size (mm×mm)	375×375	300×300
		Main reinforcement	8-15M	4-20M
6 Storey building	Up to 3rd floor	Size (mm×mm)	450×450	300×300
		Main reinforcement	8-25M	6-20M
	3rd floor to roof	Size (mm×mm)	450×450	300×300
		Main reinforcement	8-20M	4-20M
8 Storey building	Up to 3rd floor	Size (mm×mm)	500×500	300×300
		Main reinforcement	8-25M	6-25M
	3rd floor to roof	Size (mm×mm)	500×500	300×300
		Main reinforcement	6-25M	6-20M

(c)

Storey Id.	Beam ID	Size	Section ID					
			Section 1-1		Section 2-2		Section 3-3	
			Top	Bottom	Top	Bottom	Top	Bottom
3 storey building	B1	300×450	2-20M	2-20M	2-20M	2-20M	2-20M	2-20M
6 storey building	B1	300×500	3-25M	4-25M	3-25M	4-25M	5-25M	4-20M
	B2	300×500	2-20m	2-20M	2-20M	3-20M	2-20M	3-20M
8 storey building	B1	300×500	3-25M	4-25M	3-25M	4-25M	5-25M	4-20M
	B2	300×500	3-20M	3-20M	3-20M	3-20M	3-20M	3-20M

(d)

Fig. 1 Typical building configuration (a) Plan, (b) Elevation, (c) columns dimensions and reinforcement and (d) beams dimensions and reinforcement, Alam *et al.* (2012)

2.1 Structures and roof modeling

The seismic behavior of the structures was modeled using SeismoStruct (SeismoSoft 2012). 9 frame structures were modeled as planar frames. The program was used to determine the structural demands in the frame elements due to the application of the combination of loads and earthquake accelerations. The material properties, element sections, and loads were input in the software. The slabs were modeled as a distributed mass on the beams. Gravel flat roofs and green roofs are considered installed on the same roofing assembly. Therefore, to simplify the model, they were represented as dead loads. These different types of roofs were modeled as uniformly distributed load on the roof beams. The gravel roof and the green roofs were only modeled as dead loads as they are not individual structural elements rather they are attached to the roof of the building frame; therefore, the behavior of each roof type per se during a seismic event was not analyzed.

Some additional structural modeling information is as follows. Seismostruct (2012) uses fiber modeling approach instead of lumped plasticity model. The fiber modeling can take the spreading of nonlinearity along the length of the element into account. The strength of the structural materials was chosen by the authors while the frames were designed as per CSA A23.3-04 standard and using NBCC (2005) code provided loading values. The stiffness and deformation capacities of the structural members were determined from the fiber analysis of the elements using material hysteresis models available in Seismostruct (2012). For example Mander *et al*. (1988) confined concrete model was used for confined concrete's constitutive relationship and for cyclic behavior Martinez-Rueda and Elnashai (1997) proposed rules were used. Bilinear Kinematic Steel model was used for the reinforcement present in the concrete frame elements. The deformation capacities of the structural members were also calculated from the material stress-strain curves. The fracture strain of the reinforcement steel is assumed 6% and for concrete the ultimate and fracture strains were calculated using Mander *et al*. (1988) model, which calculates these strain levels based on amount of confinement steel present in the concrete. Stiffness degradation under cyclic loading is automatically taken into consideration using these models in Seismostruct (2012). P-delta effect is automatically considered in this software when each structural element is subdivided into 2-3 members. The above mentioned calculation is done through the employment of total co-rotational formulation developed and implemented by Correia and Virtuoso (2006).

The following gravitational loads were considered: Self weight of the structural elements such as slabs, beams and columns and green roof load. In addition, the NBCC (2005) suggests a live load and snow load of 4,8 kPa and 1,6 kPa, respectively. The weight of each type of green roof varies with the material and water saturation. Fully saturated green roofs were considered as the

Table 1 Weight of the different types of roofs (Based on Xeroflor 2011)

	Saturated weight (kg/m^2)		
Layers	Gravel flat roof	Extensive green roof	Intensive green roof
Root Barrier	-	0.47	0.47
Drainage and filter	-	0.80	0.80
Water retention	-	10.3	2.65
Growing medium and vegetation	-	37	225
Gravel	30	-	-
Total	30	48.57	228.92

Table 2 Weight of the RC frames

	Weight (kN)								
	3 storey			6 storey			8 storey		
	Gravel	Extensive	Intensive	Gravel	Extensive	Intensive	Gravel	Extensive	Intensive
Roof	18.39	29.77	140.36	18.39	29.77	140.36	18.39	29.77	140.36
Total*	1886	1897	2008	3911	3922	4033	5315	5327	5437
Green roof weight contribution (%)	-	1.57	7.00	-	0.76	3.48	-	0.56	2.58

*Note: The total weight is the sum of the weights of slabs, beams, columns and the green roof

worst case scenario. Additionally, the thickest intensive green roof and the thinnest extensive green roofs available in the market were analyzed. Table 1 shows the materials, layers and weight considered in the analysis (Xeroflor 2001). In addition, the weight of each RC frame considering the different types of roofs was estimated and is shown in Table 2.

3. Dynamic time history analysis

Twenty real earthquake records were selected to conduct dynamic time-history analyses for each frame to predict and compare their seismic performances. The spectrum-compatible real accelerograms were randomly selected from the Pacific Earthquake Engineering Research Center (PEER 2007) strong motion database. The ground motion data is detailed in Table 3.

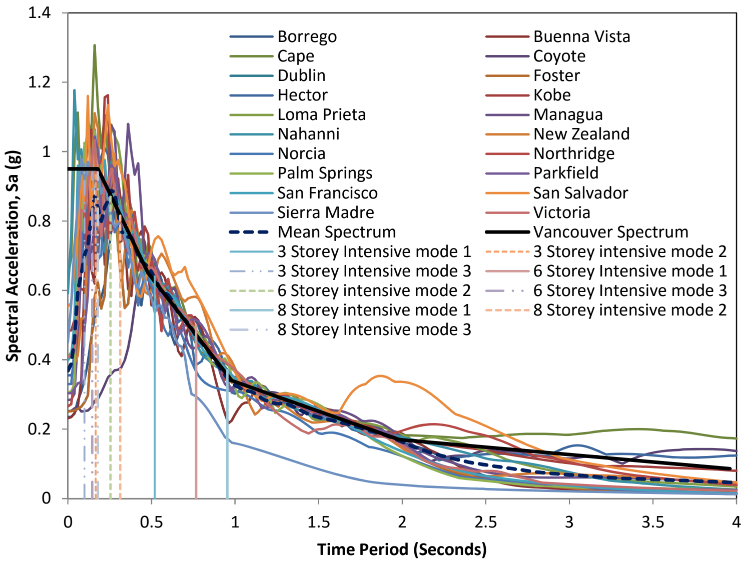
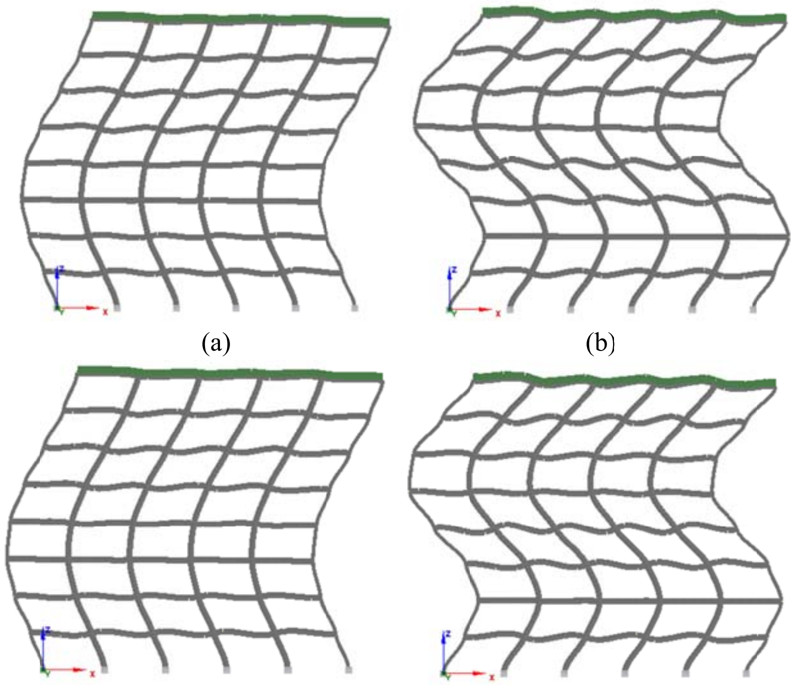


Fig. 2 Response spectra of the matched earthquake records plotted with the first three modal time periods of the intensive green roof frames calculated using cracked element stiffness's

The ground motions presented in Table 3 were scaled to match the 5% damped Vancouver soil class “C” response spectrum provided in NBCC (2005). The spectrum matching was done using Seismomatch (2012) software which uses wavelet algorithm proposed by Abrahamson (1992) and Hancock *et al*. (2006). The scaled records are plotted with respect to the design spectral acceleration for Vancouver (NBCC 2005) as shown in Fig. 2. This plot also shows the first three modal time periods of the intensive green roof frames calculated using the cracked element stiffness’s. The modal mass participation percentage for first three modes is shown in Table 4. To avoid cluttering, Fig. 2 and Table 4 only presents modal data for the first three modes of 3, 6 and 8 storied intensive green roof option.

In order to better understand the impact of the green roof on the dynamics of these building frames, the second and third modes of the eight storied frame for gravel and intensive green roof is plotted in Fig. 3. From this figure it can be clearly seen that the intensive green roof doesn’t have any noticeable impact on the dynamic mode shape of the building. Also, it was observed that there is no impact of the green roofs in the top stories of these frames particularly in terms of the second and third modes of vibration. Furthermore, from the modal mass participation calculation the following information was found. The first, second and third modes mass participation percentage for gravel roof is as follows 81.16%, 10.53% and 3.73%. On the other hand, for intensive green roof the values are 81.13%, 10.55% and 3.74% respectively. So, there is almost no difference between them.



(a) (b)

(c) (d)

Fig. 3 Higher mode shape comparison for eight storied frame between gravel and intensive roof (a) second mode (gravel roof) (b) third mode (gravel roof) (c) second mode (intensive green roof) (d) Third mode (intensive green roof)

Table 3 Ground motion records (Source: PEER strong motion database, http://peer.berkeley.edu)

Record	Event	Year	Station	M[a]	R[b] (km)	PGA (g)
1	Northridge	1994	Beverly Hills - 14145 Mulhol	6.7	9.4	0.430
2	Cape Mendocino	1992	Cape Mendocino	7	7	13.478
3	Victoria, Mexico	1980	Chihuahua	6.3	19	0.118
4	Coyote Lake	1979	Halls Valley	5.8	33.8	0.043
5	Hector Mine	1999	Amboy	7.13	43	0.198
6	Kobe, Japan	1995	Takarazuka	6.9	19.1	0.670
7	Loma Prieta	1989	Corralitos	6.9	3.9	0.498
8	Nahanni, Canada	1985	Site 2	6.7	4.9	0.389
9	San Salvador, El Salvador	1985	Geotech. Investig. Center	5.8	6.3	0.556
10	Sierra Madre	1991	LA-Obregon Park	5.61	27.4	0.203
11	Managua, Nicaragua	1972	Managua-ESSO	6.2	4.1	0.418
12	New Zealand	1987	Matahinia Dam	6.6	16.1	0.282
13	Gilroy	2002	Dublin	4.9	87	0.0069
14	Gilroy	2002	Foster City - Bowditch School	4.9	86.4	0.007
15	Parkfiled	1966	Cholame - Shandon Array #12	6.2	17.6	0.0614
16	Norcia, Italy	1979	Cascia	5.9	4.6	0.171
17	San Fernando	1971	Borrego Springs Fire Station	6.6	214.3	0.0096
18	San Fernando	1971	Buena Vista	6.6	112.5	0.0117
19	Palm Springs	1986	Desert Hot Springs	6.1	6.8	0.309
20	San Francisco	1957	Golden Gate Park	5.3	9.6	0.111

[a]Magnitude
[b]Closest distance to fault rupture

Table 4 Modal mass participation percentage for 3, 6 and 8 storied frame with intensive green roof

Number of Stories	Mode number	Time Periods (Cracked stiffness)	% Mass participation
3 Storey	1	0.658	85.48
	2	0.196	11.39
	3	0.112	1.66
6 Storey	1	0.959	80.69
	2	0.319	11.34
	3	0.174	4.14
8 Storey	1	1.231	79.15
	2	0.404	11.37
	3	0.224	4.09

Table 5 Elastic cracked and un-cracked period of the structures

	Gravel roof			Extensive			Intensive		
Frame storeys	3	6	8	3	6	8	3	6	8
T_1 from Code	0.390	0.655	0.813	0.390	0.655	0.813	0.390	0.655	0.813
Elastic (sec)	0.452	0.692	0.873	0.454	0.694	0.875	0.478	0.713	0.893
Cracked (sec)	0.622	0.929	1.202	0.625	0.932	1.205	0.658	0.959	1.231
Variation w.r.t. gravel roof, elastic period (%)				0.44	0.29	0.23	5.75	3.03	2.29
Variation w.r.t. gravel roof, cracked period (%)				0.48	0.32	0.25	5.79	3.34	2.41

3.1 Time period

The fundamental periods of the structures were determined by considering both cracked and uncracked sections. The elastic cracked period was estimated by reducing the inertia of beams and columns. The American Concrete Institute (ACI, 2008) suggests the use of modification factors 0.3 and 0.7 for rectangular beams and columns, respectively, to decrease the inertia of each element and model cracked sections. Table 5 shows the elastic period of the structures for uncracked and cracked condition. Additionally, Table 5 provides the code prediction values for period (T_1) as per the National Building Code of Canada (NBCC) 2005.

The elastic periods of the structures were close to the code prediction. However, the 6 storey frame with gravel roof was the closest to the code prediction. Additionally, for all the frames, the cracked period compared to the corresponding elastic period, is significantly higher.

The analyses results show that the installation of green roofs increases the fundamental period of the structure in comparison to the structures with gravel roof. As the mass increases, the period of the structure increases. Furthermore, results show that the differences between the fundamental periods of the buildings with gravel flat roofs, extensive and intensive green roofs decrease with the increase in number of stories. For instance, the 3, 6 and 8 storey structures with intensive green roofs have 5.75%, 3.03% and 2.29% higher elastic period, respectively compared to those of gravel roofs. Cracked periods were found to follow a similar trend.

3.2 Inter-storey drift ratio demand

The inter-storey drift ratio (ISDR) demand was computed from the dynamic time history analysis output. Results are shown in Figs. 4-6. The results show that for all roof types, the maximum demand is in the same floor level. For the 3 storey frame, on average, the maximum inter-storey drift is experienced in the first and second floor, while for the 6 storied it is fourth and fifth floor and for the 8 storey frame the maximum drift takes place, on average, in the fifth floor. For the 3 storey frames, the average maximum ISDR is 0.0099, 0.0099 and 0.0102 for gravel, extensive and intensive roof respectively; while for the 6 storey frames, these values are as follows: 0.0076, 0.0077 and 0.0079. (Figs. 4 and 5). In the case of 8 storey, the average maximum ISDR was found to be 0.0081, 0.0081 and 0.0083 for gravel, extensive and intensive roof respectively (Fig. 6). In general, extensive and intensive green roof types increase the maximum

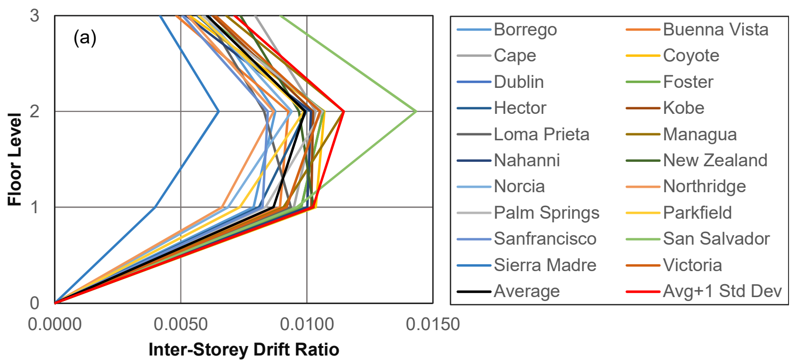


Fig. 4 Inter-storey drift demand of 3 storey (a) gravel roof, (b) extensive and (c) intensive green roofs

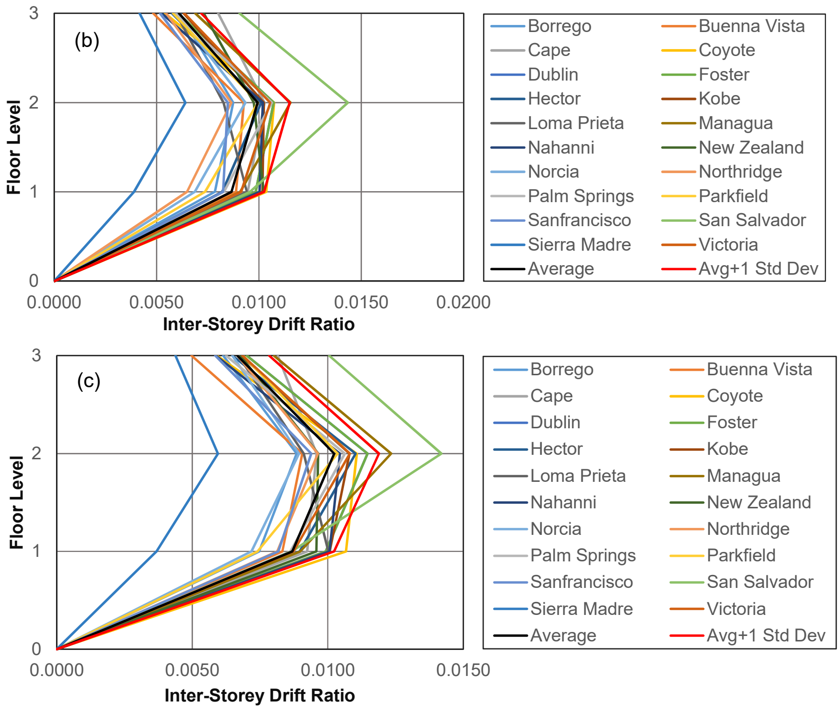


Fig. 4 Continued

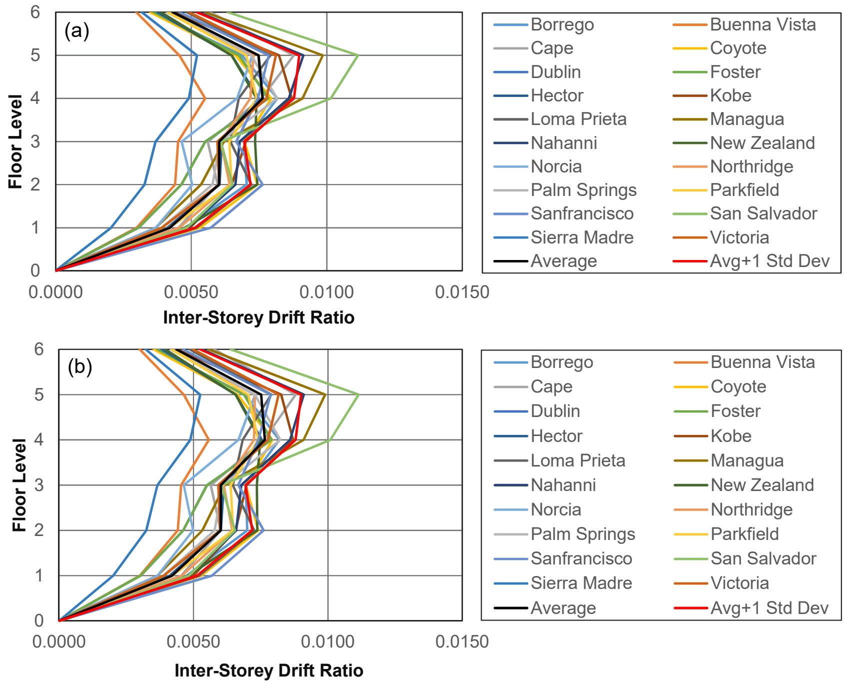


Fig. 5 Inter-storey drift demand of 6 storey (a) gravel roof, (b) extensive and (c) intensive green roofs

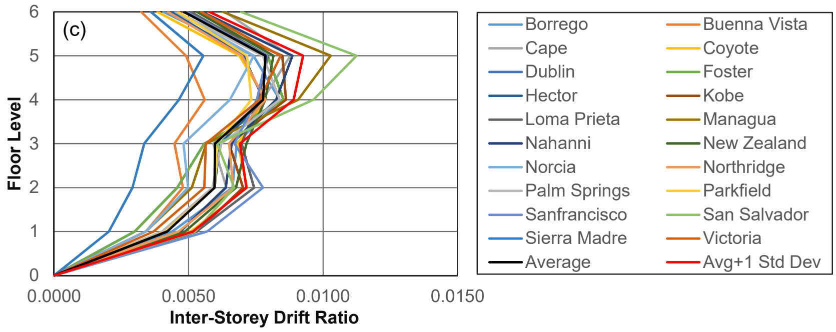


Fig. 5 Continued

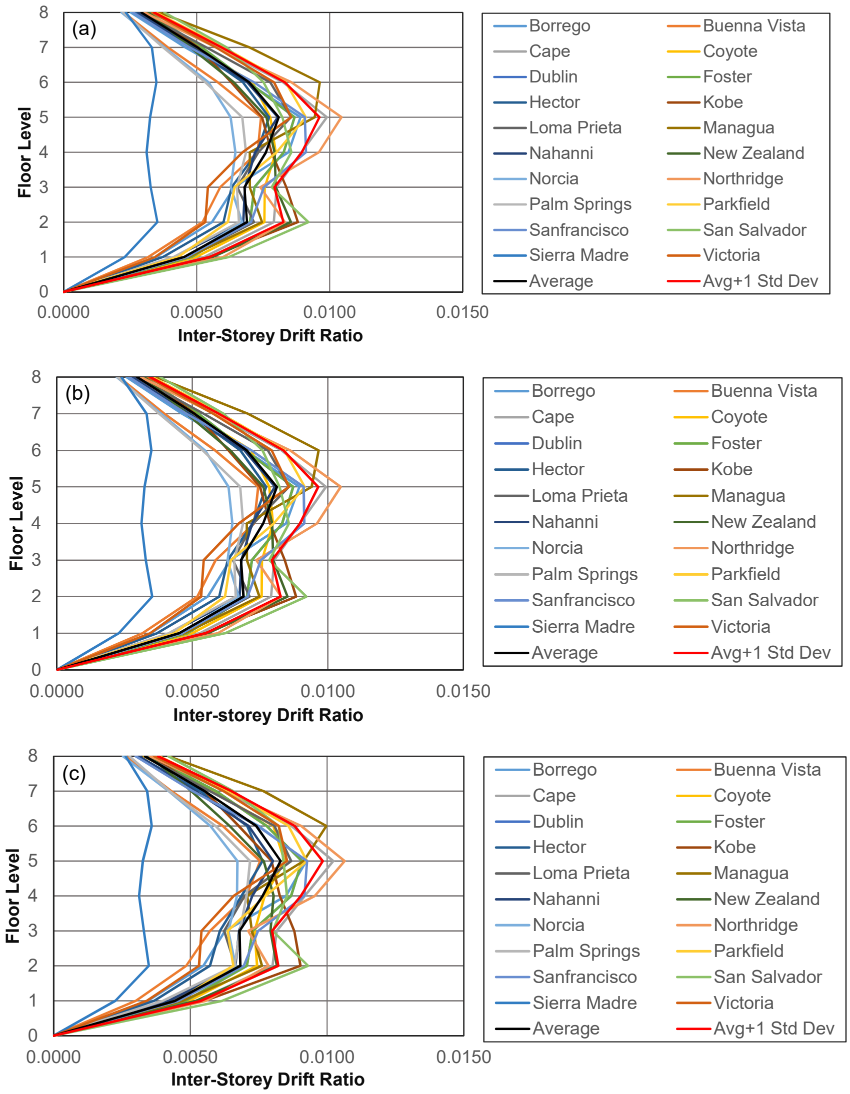


Fig. 6 Inter-storey drift demand of 8 storey (a) gravel roof, (b) extensive and (c) intensive green roofs

ISDR compared to that of gravel flat roof type by a very insignificant amount. For instance, intensive green roof of the eight storied frame increased the average maximum ISDR demand by 2.4% compared to the gravel roof.

None of the inter-storey drifts exceeded the NBCC (2005) limit of 0.025. The low inter-storey drift values indicate that the installation of green roofs do not pose any detrimental effect on the seismic behavior of the structural system.

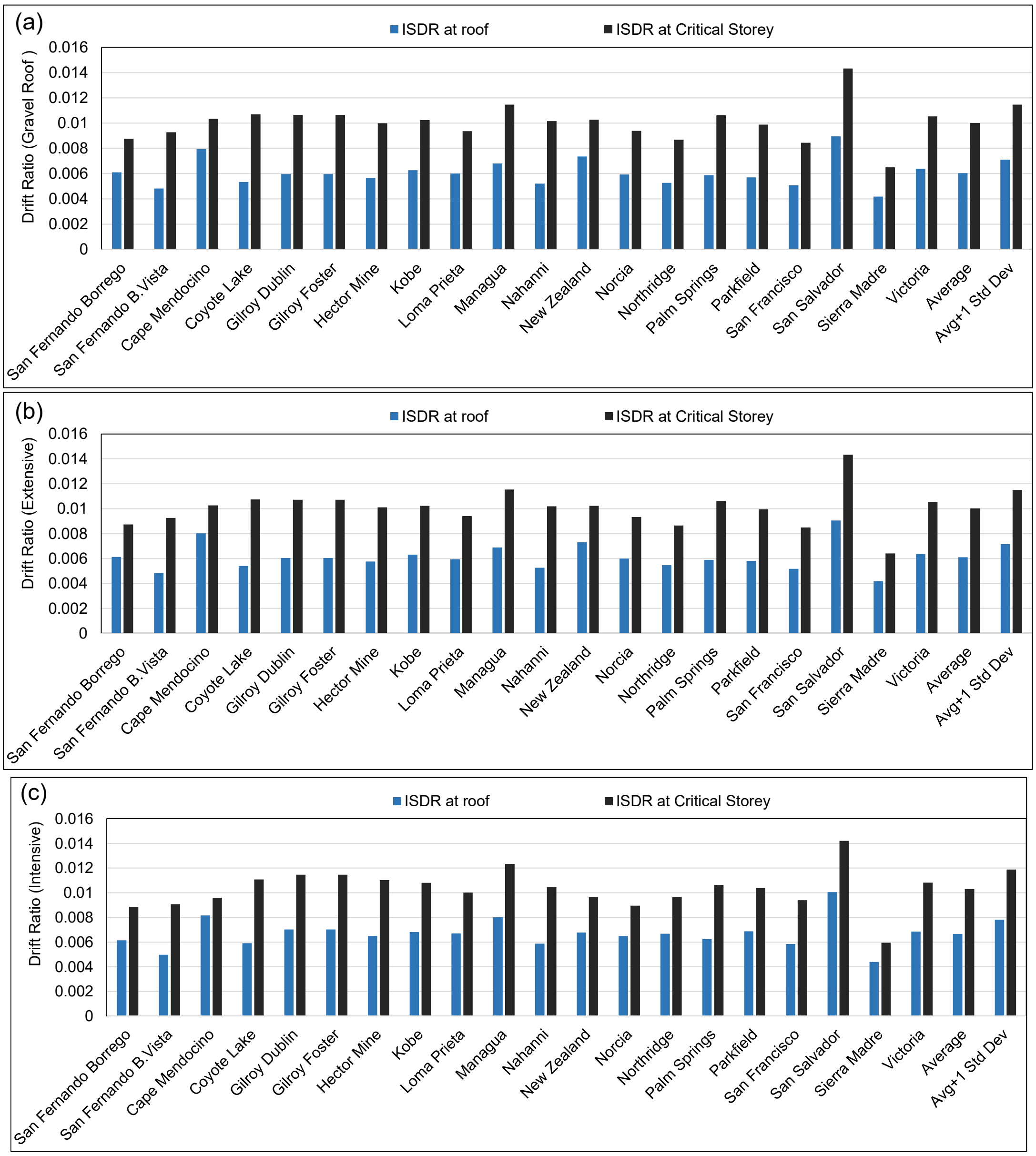


Fig. 7 Inter-storey drift ratio demand at roof and at critical storey level of 3 storey frames for (a) gravel roof (b) extensive green and (c) intensive green roof

3.3 ISDR demand at the roof and critical storey

Figs. 7-9 compare the ISDR demand of the roof storey and critical storey (the storey with the maximum ISDR) obtained for all the frames with different roof types under the selected earthquake motions. In the case of 3 storey frame (Fig. 7), on an average, intensive green roof caused the highest roof and critical storey drift compared to those with other roof types, but the difference between them was found to be insignificant. Similar trend was observed for the 6 and 8 storey frames (Figs. 7(b)-(c)).

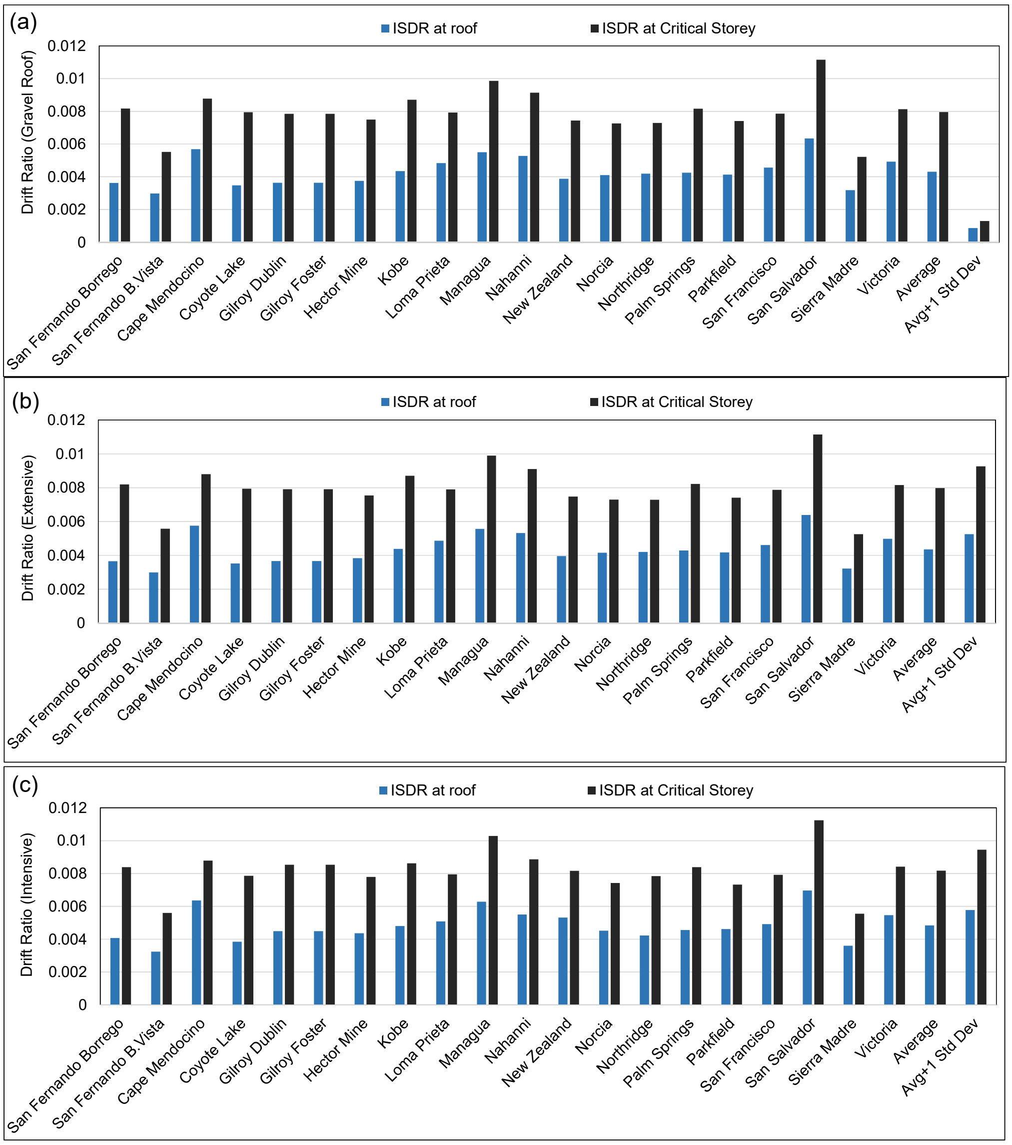


Fig. 8 Inter-storey drift ratio demand at roof and at critical storey level of 6 storey frames for (a) gravel roof (b) extensive green and (c) intensive green roof

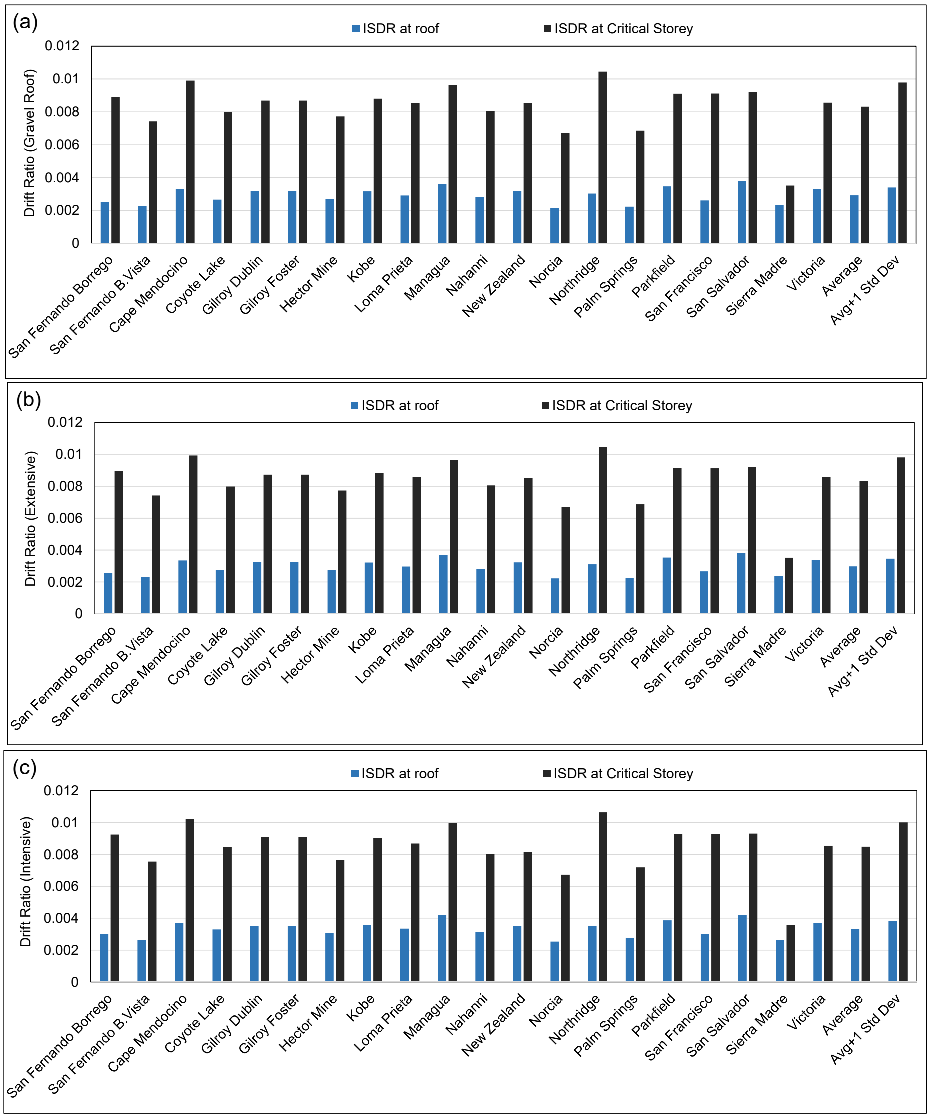


Fig. 9 Inter-storey drift ratio demand at roof and at critical storey level of 8 storey frames for (a) gravel roof (b) extensive green and (c) intensive green roof

From Figs. 7-9 it can be observed that in the case of 3 storey frame, the demand ISDR at roof of extensive and intensive green roof is 0.9% and 10.3% higher than the gravel roof. In the case of the 6 storey frame, extensive and intensive green roofs increase the roof storey drift by 1.10% and 12.13% respectively. The 8 storey frame follows the same trend as that of the 6 storey frame. Compared to gravel flat roofs, extensive and intensive green roofs increase the roof storey drift by 1.37% and 13.9%, respectively. In general, as shown in Figs. 4-6, as the frame height increases the roof storey drift demand decreases. Additionally, the difference between roof storey drift demands of the same storey frame with different roof types is also significant.

The seismic performance should be evaluated by comparing the capacity of the RC frames with

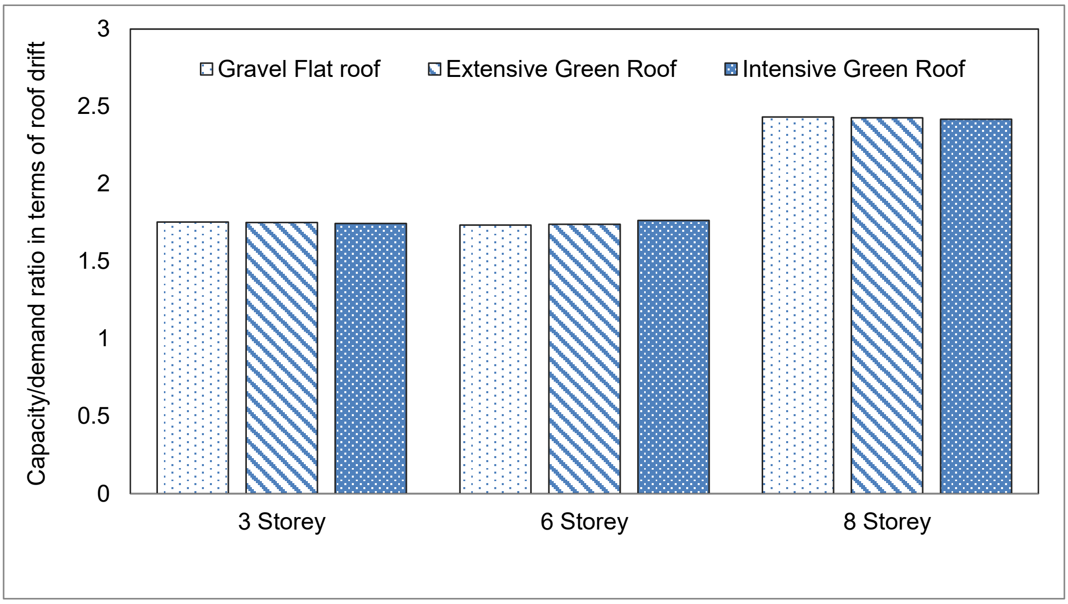


Fig. 10 Roof drift capacity/demand ratio

that of the demand that those frames experience under a seismic event. The roof drift capacity is determined from a pushover analysis, while the demand is estimated by a dynamic time history analysis. From pushover analysis the roof drift capacities of the three, six and eight storied frames used in this study are 0.169 m, 0.207 m and 0.393 m respectively (Alam *et al*. 2012).

Fig. 10 shows the roof drift capacity/demand ratio for all the frames with different roof types. Results show that the capacity/demand ratios remain fixed for a selected frame height for all the roof types. But it is clearly seen that the eight storey frame has approximately 40% higher roof drift capacity/demand ratio compared to both four and six storied frame. In conclusion, the results show that all the frames have a higher than 1.7 roof drift capacity demand ratio for all the earthquakes considered in this study.

4. Conclusions

RC frames with three different heights (e.g., 3, 6 and 8 storey) and roof types (e.g., gravel, extensive and intensive) have been analyzed. Dynamic time history analyses were conducted on all the frames to determine the capacity/demand ratio in terms of roof drift ratios. Results demonstrate the impact of green roofs on the seismic performance of the frame structures in terms of change in fundamental time period, maximum inter-storey drift ratio, top storey drift demand and roof drift demand/capacity ratio. In the case of 3 storey frames:

• On average, the maximum inter-storey drift is experienced in the first and second floor. The average maximum ISDR demand is around 0.0102 for all roof types.

• The roof storey drift caused by intensive and extensive green roof is 10.32% and 0.923% higher than that of gravel flat roof, respectively.

In the case of 6 storey frames:

• On average the maximum inter-storey drift takes place on the fourth floor. Intensive green roof causes the average maximum ISDR demand (0.0079).

• The roof drift caused by intensive and extensive green roof is 12.13% and 1.10% higher than that of gravel flat roof, respectively.

In the case of 8 storey frames:

• The average maximum inter-storey drift experienced is 0.0083 in the fifth floor for the intensive green roof.

• The roof drift caused by intensive and extensive green roof is 13.88% and 1.37% higher than that of gravel flat roof, respectively.

The dynamic time history analyses reveal that green roofs have some impact on the dynamic behavior of frame structures especially at the top storey; however, the impact is not very significant. Based on the findings, no retrofitting technique is required to increase the lateral strength or deformation capacity.

For the range of extra added load considered in this study this research found out that the regular frames under investigation performed satisfactorily against seismic loading. This performance might be attributed to the fact that these structures were properly designed according to current seismic design code. However, for different geometries and green roof load ranges (not considered in this study) one must carry out extensive analysis prior to the installation of green roofs. Furthermore, prior to the implementation of green roofs, analysis must be carried out to determine the capacity of the structural elements to resist the increase in gravitational loads due to the extra weight coming from the green roof. Nevertheless, it is difficult to opine that a green roof will not pose a risk to the frame structure that has a top story which can develop significant nonlinear behavior during the design ground motion. Previous studies have shown that the effect of higher modes can lead to excessive damage in the top stories. Under these circumstances, the addition of a green roof may be a problem and needs careful investigation before implementation. Further research is required to determine the seismic performance of structures in the case of partial green roofs on plan dimensions and arrangements.

There is a greater need to implement clean technologies that enhance quality of life and save energy. Green roofs represent an engineering effort that contributes towards environment friendly practices. Facilitating and expanding their installation on new and existing buildings is an imperative step in green design and construction.

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