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Seismic Response of a 3-Story Green Roof Steel Structure

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ABSTRACT

Sustainable detailing such as material selection, greywater systems, and green roofs reduce a structure's impact on the environment but they do not reduce the impact of the environment on structures. To date, limited work has investigated the structural implications of these new sustainable features. This is especially true for green roofs which add significant weight to the roof level. These roofs consist of layers of soil and vegetation used for recreational purposes as well as water management. This study takes the first crucial step in investigating the seismic response of a two-dimensional, 3-story steel moment resisting frame with a green roof. Using OpenSees, dynamic analyses are performed for a suite of ground motions, near and far fault excitations, from the PEER database. For each ground motion, three models are considered – (a) control, the frame without a green roof; (b) frame with a shallow green roof and (c) frame with a deep green roof. The two green roof profiles differ by the depth of the soil layer and vegetation. To evaluate structural performance, floor displacements and accelerations at each level are investigated and compared for the three models. The preliminary results show minimal decrease in floor level displacements. However, the decrease in floor level accelerations is far more significant with the potential to improve the performance of structural content such as equipment and machinery. These results present the general trends to initiate the discussion of optimizing green roofs for structural dynamic control to achieve performance and resilience goals.

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1. INTRODUCTION

In recent decades, there has been increasing interest towards sustainability with respect to environmental protection. According to the United States Department of Energy (US DOE), between extraction of the resources, manufacturing, construction and operation, buildings are the major consumer of energy (US DOE 2012). As the building industry addresses that fact and goes beyond minimal requirements for design and operation of the buildings, the rating systems such as LEED were created to evaluate the performance of green buildings (US Green Building Council 2009). In evaluating and studying the environmental benefits of green buildings, most of the attention goes towards thermal benefits and stormwater management (Vijayaraghavan 2016). One such element addressing these sustainable objectives is a green roof, a roof with vegetation planted in an appropriately engineered substrate (Vijayaraghavan 2016). These roofs help with rainwater capture and runoff maintenance while providing layers of insulation and creating a habitat for many species of insects and birds (Wang et. al. 2017). Examples of such roofs worldwide include the California Academy of Sciences in San Francisco, Chicago City Hall (Fig. 1), and the Multipurpose Hall on Jeju Island.

Fig. 1 Chicago City Hall Green Roof (Pursuitist 2015)

However, in the structural engineering field, this movement is followed by the statement that sustainability reduces the impact of a structure on the environment but does not reduce the environment’s impact on a structure. As a result, the goal of resilient designs is to increase the life of a building and its post-event functionality which are crucial for the sustainable performance of the structure. Sustainable structures such as green roofs incorporate resource efficient systems and environmentally friendly materials. These systems can introduce complexities, such as additional and variable weight, to the structural design.

Two studies in particular studied green roofs as a seismic response mitigation device, such as a tuned mass damper or TMD (Matta 2019a; 2019b). In the first study, Matta and Stefano (2019a) considered the performance of the green roof as mass-uncertain rolling-pendulum tuned mass damper (PTMD) in comparison to traditional TMD. In their later paper, Matta and Stefano (2019b) evaluated if PTMD or translational tuned mass damper (TTMD) is preferable for mitigating seismic response. These two studies are focused on the design and performance of TMDs and their effect on the structural response of the building. However, neither of these looked at the implications of the mass alone on the structural response. Before we can begin to evolve the use of this mass, it is crucial to understand the basic dynamics of the response.

To explore both sustainability and resilience, this project initiated the investigation into the seismic performance of a three-story steel structure with a green roof using numerical models with focus on floor displacements and accelerations.

2. STUDY APPROACH

Modeling the green roof as a fixed mass, there were three models considered: (a) **control frame** (CF), the frame without a green roof; and the frames (b) with a **shallow green roof** (SGRF) and (c) with **deep green roof** (DGRF). The last two differ by the depth of the soil layer and types of plants impacting the amount of mass considered.

The modeled structural frame (Fig. 2) is made of steel and is assumed to remain elastic which is consistent with current seismic isolation design approach. The 2D structure is 3-stories (39 ft) tall and 4-bays (120 ft) wide (McCallen 2003). This structure was derived from a full 3D structure consisting of 120-ft steel moment frames at each side of the building and intermediate gravity frames spaced at 30 ft. Only the exterior moment frames resist the seismic load. The outside columns of the frames are W14x159, the inside columns are W14x176, and the beams are W24x84, W24x76 and W24x68 for the second floor, third floor and roof respectively. The total tributary weight of the frame is 1900 kips.

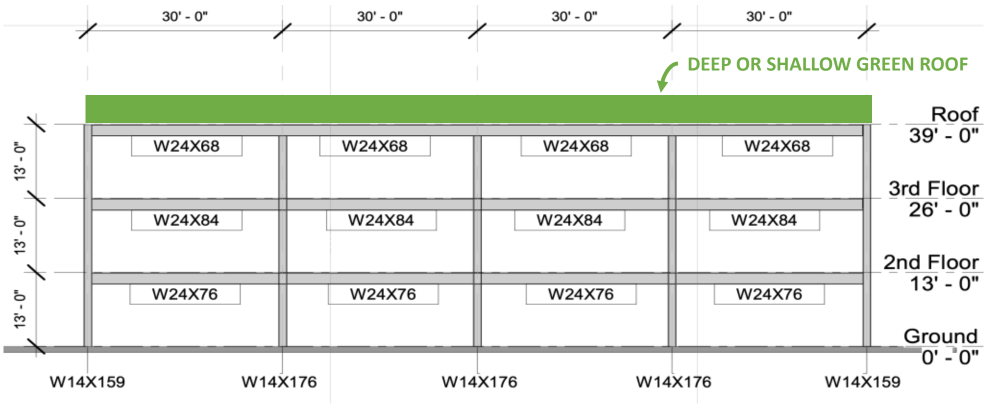

Fig. 2 Three-story Steel Moment Frame with Green Roof

For the shallow and deep green roof, added mass was introduced at the roof level. The green roof frames differed by the presence of additional mass on the top beam members. The widely used classification for the green roofs is adopted from Welsh-Huggins and Liel (2017), where the roofs are classified by the depth of the substrate. The shallow roof was defined as having a soil depth of no more than 6 inches, and the soil depth ranges from 8 to 24 inches for a deep green roof. The average dead loads for shallow and deep roofs were also taken from the above study and were 47.9 psf for the shallow green roof and 200 psf for the deep green roof.

For this initial study, the 1995 Kobe earthquake was used for the dynamic analyses. These motions were taken from the PEER database (Ancheta et. al. 2013) at three distances from the fault (0mi, 15.5mi, and 31mi) to understand the sensitivity of response to fault proximity. The motions had peak ground accelerations (PGAs) of 0.70g, 0.21g, and 0.09g respectively and were only applied uni-axially in the horizontal direction.

All modeling and computational analyses were conducted in the open source software – OpenSees (McKenna Fenves 2000). Spectral analysis was performed using SPECTRA (McCallen 1991), a Fortran program. Post-processing of results was conducted using MATLAB and Excel.

3. RESULTS

To get a baseline understanding of the varying structural dynamics of these three models, an eigenanalysis was first performed (Table 1). As seen in the table, the general result is an increase in the periods, as expected, due to the increasing presence of mass at the roof level. Based on these modal values, Rayleigh damping coefficients anchored to the first and third modes were calculated assuming a damping ratio of 5%.

Table 1. Three-story Steel Moment Frame with Green Roof

Model:	**Period, s**			**Frequency, Hz**		
	I	**II**	**III**	**I**	**II**	**III**
CONTROL	0.9125	0.2863	0.1677	1.0958	3.4924	5.9623
SHALLOW	0.9531	0.2959	0.1689	1.0493	3.3795	5.9190
DEEP	1.0743	0.3165	0.1710	0.9309	3.1599	5.8477

Next, the three models underwent dynamic analyses to provide insight into their seismic response.

The results for the floor displacements are provided in Fig. 3 and Table 2. The displacements of the floors for the control, shallow and deep green roof frames increased with the height of the floors. Looking at the change in displacements between the three models introduced some interesting results. Firstly at 0mi, the inclusion of the green roof decreased the maximum displacement by 5% at most on the lower floors with the deep roof providing minimal improvement. Next looking at the results at 15.5mi, the best results are from the use of a shallow roof with the greatest decrease of 7% at the 2nd floor. The deep roof in fact increases the displacements at the roof floor but at a rate of 2%. Lastly, at 31mi, the greatest reduction occurs with the deep roof at 35% improvement with the shallow roof actually increasing the max displacement at the roof level. Overall, these results shows minimal improvement of the displacements with the inclusion of the green roof except in the far field (31mi). However, looking at the magnitude of the displacements with the control frame, the improvement percentage is high but most likely not very noticeable in the structural system. As displacements alone should not be the only metric for evaluating structural performance, next we will investigate the impact these roof models have on accelerations.

Table 2. Floor Displacements (Kobe 1995) with Lowest Displacements Highlighted

	Kobe (0mi)			**Kobe (15.5mi)**			**Kobe (31mi)**		
	2nd	**3rd**	**Roof**	**2nd**	**3rd**	**Roof**	**2nd**	**3rd**	**Roof**
Control	3.69	8.40	11.28	2.56	5.97	8.13	0.33	0.68	0.86
Shallow	3.59	8.27	11.23	**2.38**	**5.60**	**7.73**	0.31	0.65	0.92
Deep	**3.51**	**8.06**	**11**	2.55	5.90	8.30	**0.22**	**0.34**	**0.56**

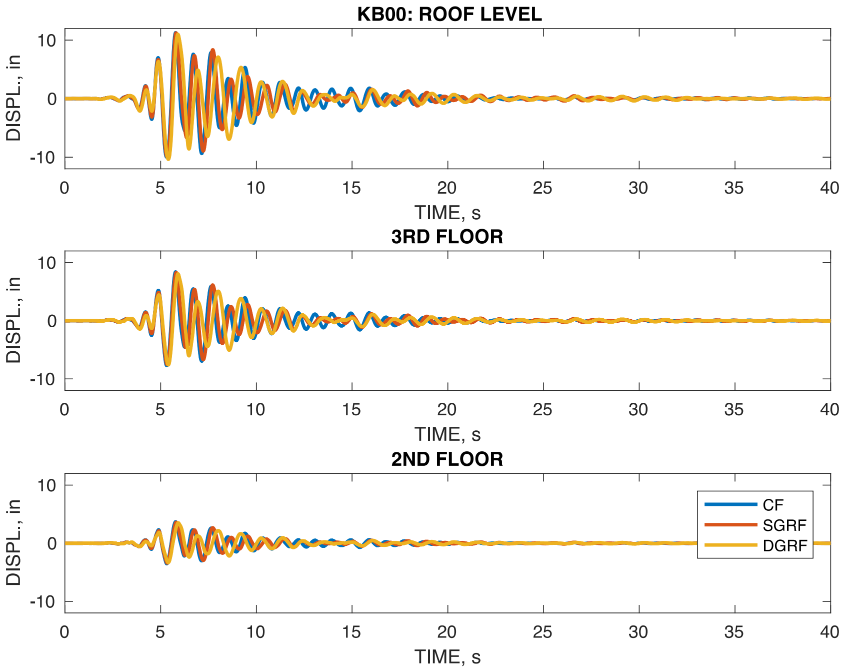

Fig. 3 Floor Displacements shown at the Roof (top), 3rd Floor (middle), and 2nd Floor (bottom) for the Three Models for Kobe (0mi)

Table 3. Floor Accelerations (Kobe 1995) with Lowest Accelerations Highlighted

	Kobe (0mi)			**Kobe (15.5mi)**			**Kobe (31mi)**		
	2nd	**3rd**	**Roof**	**2nd**	**3rd**	**Roof**	**2nd**	**3rd**	**Roof**
Control	0.78g	1.05g	1.47g	0.36g	0.70g	1.1g	0.15g	0.14g	0.18g
Shallow	**0.71g**	0.97g	1.39g	**0.30g**	**0.58g**	0.96g	**0.14g**	**0.14g**	0.18g
Deep	0.72g	**0.87g**	**1.03g**	0.35g	0.58g	**0.75g**	0.14g	0.15g	**0.13g**

To understand the effects on the absolute accelerations of the system, this response was looked at from two perspectives: time history and response spectra. First looking at the absolute accelerations at each floor, we have the maximum values in Table 3 and the full time histories in Fig. 4. Having a deep green roof resulted in the decrease of accelerations of the roof level by 30% for all distances. As compared to control frame, the shallow roof decreased accelerations by 6% and 13% at 0mi and 15.5mi respectively leaving the 31mi results showing virtually no change. In the other floors, the decrease is less than 10% for the 2nd floor and less than 20% for the 3rd floor with the least improvement at 31mi.

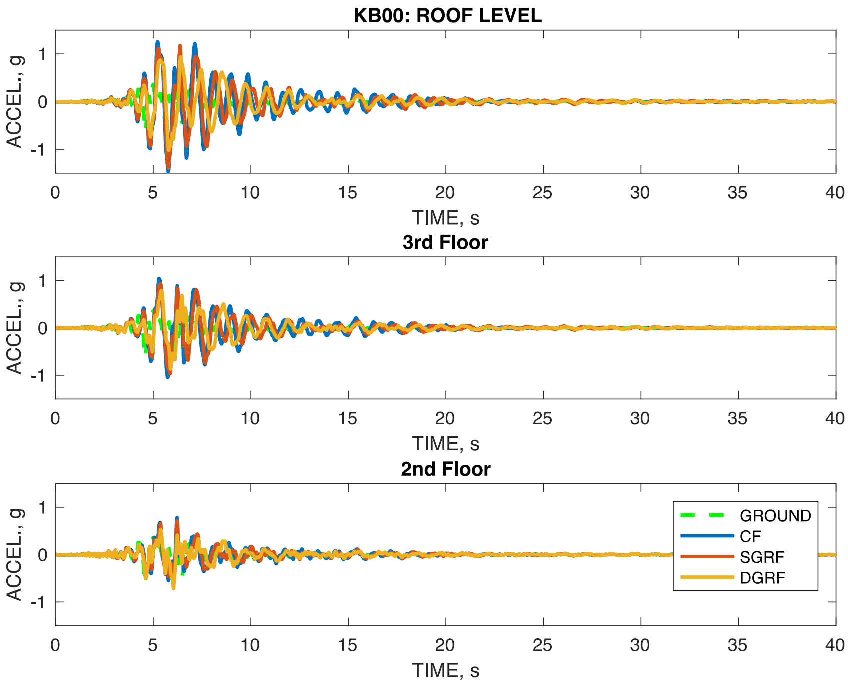

Fig. 4 Floor Accelerations shown at the Roof (top), 3rd Floor (middle), and 2nd Floor (bottom) for the Three Models

Looking at the response spectra, we will focus in on the roof level at 0mi and 15.5mi as this level saw the greatest improvements in response. As seen in Fig. 5, the two floor level response spectra look a bit different from each other. They both do exemplify the peak overall accelerations occurring around the fundamental periods of their structures. However, the spectra at 0mi are far broader than at 15.5mi. This broadening is significant as we must consider the possibility of equipment being placed at the roof levels. In most structures, key equipment essential to building operation such as HVAC are many times located at the roof level. These heavy pieces of equipment and machinery tend to fall in period ranges less than 1s. As a result, the green roof may not be entirely desirable in the near field range. Instead, its presence in the mid-field around 15.5mi would not be as detrimental. Overall though, it should be noted that the inclusion of the green roof does provide an improvement in the spectral response for periods less than 1s. For this reason, equipment and machinery would benefit with the presence of the roof even if it is a slight improvement.

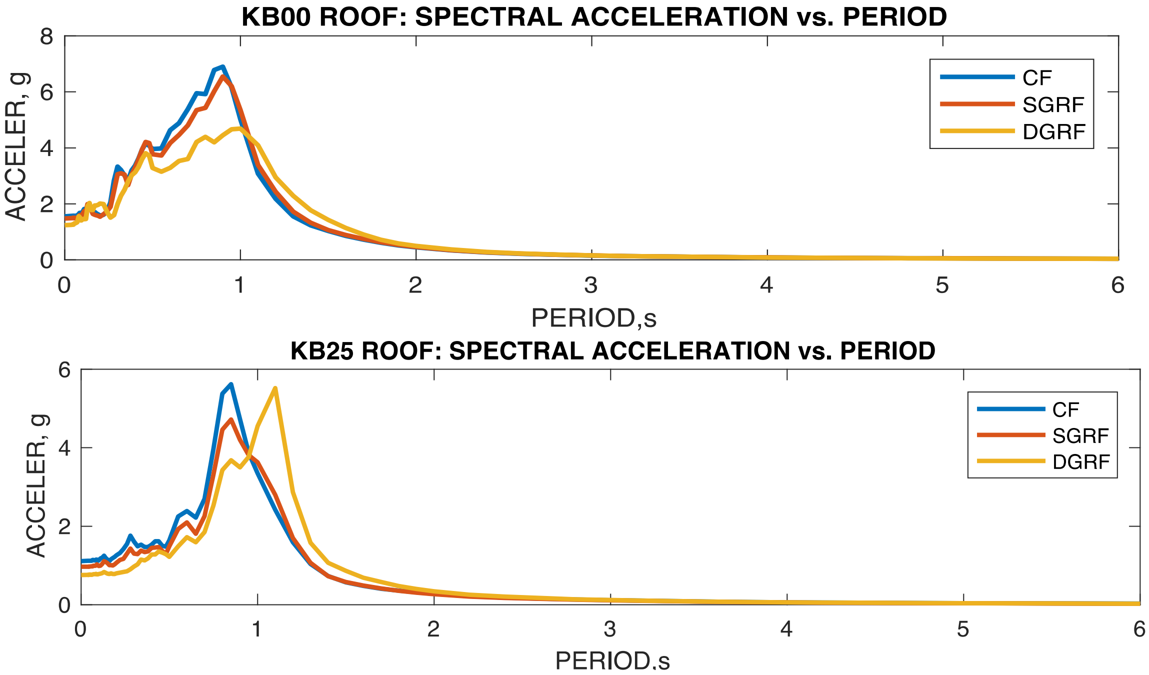

Fig. 5 Floor Response Spectra at the Roof Level Taken at 0mi(top) and 15.5mi(bottom)

4. CONCLUSIONS

This initial study has provided significant insight into the way that green roofs do and do not impact the general seismic response of a structure. In terms of its basic dynamic behavior, there is a clear increase in period as the additional mass drives this. But looking at the dynamic response from the time history analysis, the discussion is a bit more dense in understanding the ability of these systems to aide the structural performance.

Generally, the dynamic analysis shows that the addition of a green roof has minimal effect on floor displacements in the near (0mi) and mid-field (15.5mi). For the far field motion (31mi), there was significant decrease in the floor displacements but considering the displacements were not very large from the start, for the control frame, this result is less significant. Looking at the accelerations, however, provides a slightly different perspective. The addition of a green roof decreases accelerations across all floors with the deep roof providing the largest decrease across all distances. The response spectra also showed there was an improvement with the inclusion of the green roof especially for equipment and machinery that fall in the period range below 1s. The results also showed though that at locations closer to the fault, the spectra broaden similar to the control frame presenting no improvement in the spectral shape.

Based on this limited set of results, there is a case for the inclusion of a green roof to improve the seismic performance of the structure. Instead of the displacement response being the driving factor, it is actually the acceleration improvement that makes this system more viable. Depending on the purpose of the structure, the need for continued operation or quick recovery of these pieces of equipment will factor into the resilience of the overall system. With the advent of improved building codes and design, the ability of a typical control frame such as the one discussed here to successfully survive an earthquake is highly probable. This is also very evident in the performance of new and rehabilitated structures worldwide in recent events. However, although the building may be structurally sound, there is the potential for the structure to be deemed unoperational due secondary damage to equipment and machinery.

Further work is necessary to firmly establish the advantages of using green roofs to address seismic performance and resilience. It will be important to expand the discussion to a larger suite of ground motions and additional structural systems to provide a wider vantage point from which a set of recommended guidelines could be provided. This foundational work presents the initial results promoting the use of green roofs not only to improve environmental impacts but also structural resilience.

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