USE OF BASE ISOLATION AND SUPPLEMENTAL DAMPERS FOR SUSTAINABLE STRUCTURAL DESIGN OF BUILDINGS

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Abstract

In this paper, the effectiveness of seismic control devices in reducing initial embodied emissions from RC buildings is investigated within the context of sustainable structural design. The study is divided in four sections. In the first, the sustainability indicators for assessment, namely embodied energy and embodied carbon are introduced, and a definition of sustainable structural design is proposed. In the second, the seismic performance-based design of the following three buildings is presented: conventional baseline bare building, building with nonlinear viscous dampers, and base-isolated building. The buildings were subjected to a suite of 10 pairs of ground motions, and analyzed by time-history analysis. In the third section, the embodied energy and embodied carbon emitted for each individual building are calculated by using coefficients taken from an existing inventory. Then, the sustainable performance of the buildings with seismic devices is calculated by direct normalization with the baseline building. Finally, in the last section, the results and conclusions are discussed. The most significant findings suggest the use of two ways of seismic energy dissipation is the most efficient approach to achieve sustainable structural design. Although the embodied emissions from seismic devices were not included in the analysis, the results suggest there is a wide interval to allocate them without affectation in the sustainability improvements achieved. The study was conducted with the current knowledge and tools available. Therefore, it may be implemented in practicing engineering; for instance, in LEED® simulations that require sustainable structural information as input in complex integrative models.

Keywords: Sustainable structural design; Sustainable buildings; Green buildings, LEED® rating system; Seismic control devices

1. Introduction

Sustainable construction is a complex multidisciplinary task that will require some time for full practical implementation. However, there is an objective to achieve in the near future, namely the reduction of greenhouse gasses (GHGs) emissions from buildings during their life cycle. Thus, initial emissions from construction and structural materials are now assessed in approaches such as Zero Emissions Buildings, (ZEB) [1], and certification schemes such as LEED® [2] of BREAM [3], in addition to those from energy sources during building operation, and those from building deconstruction or demolition.

The reduction of initial embodied emissions is one of the most urgent challenges that structural engineering faces. For new buildings, among several sustainable-oriented strategies, reducing the size of structural members is a promising strategy to abate initial emissions in a reasonable period of time. Moreover, reducing sections may also benefit other aspects of sustainability such as open spaces, daylight rates, and thermal effects of the building envelope.

1.1 Objective and Research scope

The objective of this study is to assess the effectiveness of seismic control devices in reducing initial embodied emissions, namely embodied carbon (EC) and embodied energy (EE) in the superstructure of RC buildings. To this end, the following three-step methodology was adopted:

1. Introduction of sustainability framework and definition of sustainable structural design.
2. Performance-based seismic design of: *a)* baseline building (hysteretic dissipation), and *b)* two proposed buildings: building with seismic dampers (hysteretic dissipation+viscous damping), and base-isolated building (elastic superstructure).
3. Assessment of sustainable performance with coefficients for EC and EE taken from existing inventories.

The study was performed with the current knowledge and tools available in practicing engineering to evaluate its possible implementation in the near future. It does not investigate the financial benefits and/or deficits of the analyzed buildings. No other aspects that may influence the sustainability indicators shall be considered such as material's characteristics (e.g. thermal properties), construction procedures, preparations for deconstruction, building operation or maintenance, etc. As the author knowledge, the embodied emissions from seismic devices have not yet been made public so they were not included in the analysis.

2. Sustainability framework

Currently, there is no a worldwide agreed definition of sustainability nor its method of achievement. Most definitions of *sustainable* and *green* buildings share the principle of creating environmentally responsible places that protect the health and well-being of their occupants, with social and economic benefits (regionally and globally). Sustainable structural design is then, usually conceived as the design of sustainable buildings. To overcome this general conception that may lead to inconsistencies, in this study, the concept of sustainable structural design is derived from the performance-based design philosophy under the perspective of both, seismic-structural response and energy efficiency.

The seismic performance-based design has been extensively studied and currently, the performance objectives are well defined in codes and design specifications. On the other side, performance objectives for sustainable performance-based design have to be carefully chosen due to the large number of variables involved, and assessed by well defined metrics [4]. To be specific in the performance objectives, in this research the sustainability indicators are limited to those pertaining to the structural engineering field, and assessed by a baseline building to investigate the objectives achievement. Therefore, sustainable structural design is defined as the pattern that holistically satisfies a robust earthquake-resistant framework, and simultaneously demonstrates improvements on predefined sustainability indicator(s) against a baseline structure. Performance-based Seismic Design was adopted as earthquake-resistant framework. Embodied energy and embodied carbon, CO_2, were taken as sustainability indicators. EC is a characteristic GHG from construction industry to be urgently reduced, and EE is a related parameter to evaluate environmental impacts.

The proposed definition allows the quantitative assessment of both, structural and sustainable performance as *stand-alone* approach or within sustainable frameworks such as ZEB or LEED®. For instance, in these frameworks the superstructure may be designed to achieve an initial sustainability performance objective before input the structural information into the required external generic building models (integrative models), reducing computational costs and interaction time with other disciplines.

2.1 Sustainability indicators

Likewise other aspects of sustainability, there is no a unique method to calculate the embodied energy and embodied carbon for construction materials. These indicators are commonly measured using Life Cycle Assessment (LCA) [5] over the building's life cycle or within particular boundaries. LCA, however, is not common in practicing structural engineering as it is not only complex by nature, but also unbalanced in the criteria assessment. Therefore, in this study EE and EC for reinforced concrete were taken from an existing inventory, similarly as other research in the same field [6].

In available inventories, embodied emissions are reported based on boundaries representing the life stages of the material since its extraction until its end-of-life. Generally, they are summarized as follows: In the first stage, known as "cradle-to-gate", only the embodied emissions resulted from the product and production process are considered. The second, named "cradle-to-site", accounts for the recurrent impacts of the final material (maintenance, replacement, etc.). The third, known as "cradle-to-grave", goes beyond the useful life of the material and takes into account the end-of-life impacts (deconstruction, disposal, etc.).

Following the scope of this study, only the embodied energy required to produce reinforced concrete ("cradle-to-gate") was assessed; downstream impacts were excluded. This is valid since RC has practically null maintenance or replacement in office buildings. Therefore, the embodied energy from the ICE database [7] is adopted as the total primary energy consumed from direct and indirect processes associated with the product within the boundaries of *cradle-to-gate*. Similarly, embodied carbon is taken as the sum of carbon emissions related to fuel and production material process into the boundaries of *cradle-to-gate* [7].

3. Seismic performance-based design

In this section, the seismic performance-based design of buildings is presented. In all cases, the design meets the force requirements as closely as possible to the minimum values in order to achieve smaller structural sections.

3.1 Benchmark model

The benchmark structure was taken from reference [8]. It is the four-story, four bays framed-building shown in Fig. 1. Time-history analysis (THA) were carried out to calculate the seismic forces, so the results from baseline building (bare fixed-base building) and buildings with seismic devices could be straightforwardly compared. The design was performed with specifications ASCE-7 [9] and ACI-318 [10]. The building was assumed fixed in the base as permitted in ASCE-7 to calculate seismic forces. The loads on floors were similar to the reference [8]: *a)* for levels 1-3, dead and live loads were taken as 120.5 psf and 50 psf, respectively, and b) for fourth level, dead and live loads were taken as 125 psf and 20 psf, respectively. No other loads were considered in the analysis (including those from extreme events such as wind or snow). As a simplification that did not affect the sustainability behavior, floor slabs and slabs on grade were excluded in calculation of embodied emissions but included in the structural models.

Likewise in [8], a set of 10 ground motions were taken from the SAC Steel Project at 2% probability of occurrence in 50 years. For each record a pair was simulated, then, each pair of motions were scaled such that in the period interval from 0.2T *(or* $0.5T_D$ *for isolated buildings)* to 1.5T *(or* $1.25T_M$ *for isolated buildings)*, the average of the SRSS spectra from all horizontal component pairs did not fall below the corresponding ordinate of the design spectrum. Neither the method to scale the earthquakes nor the allowable variation between the scaled and the design spectra are specified in ASCE-7. For the objectives of this research, all models were subjected to the same seismic demand that the baseline building. Then, the earthquakes were scaled to match the design spectra at a single value, T=1.0, instead of a range of periods as Fig. 2(a) illustrates. Differences in the ordinates from ASCE-7 and scaled SRSS spectra may be anticipated for different periods. However, based on analysis with systems with T=1.05 sec [11], it seems that no significant dispersion in the engineering demand parameters is expected for the fixed-base building (uncracked period T=0.7 sec), considering the period elongation as the system responds during strong shaking (T=1.0). For the building with supplemental damping (Section 3.3), viscous dampers that do not modify significantly the structural period were used. For base-isolated building with lengthened period (Section 3.4), the difference in the spectral ordinates may be taken by the isolators damping. It is recommended, however, a careful selection of the scaling method to avoid using motion records that may not realistically represent the seismic demands on the structure.

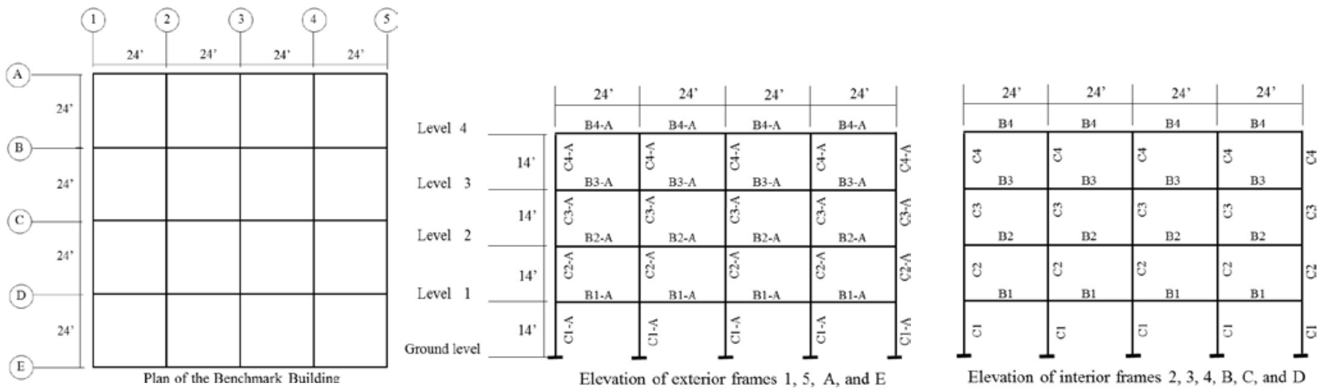

Fig. 1 – Layout of the benchmark building

3.2 Baseline building

The baseline building was classified as special moment resisting frame (SMRF). The categories for design and risk were specified as D and I, respectively. The parameters for seismic design were taken as follows: importance factor I_e=1, response modification coefficient, R_a=8, overstrength factor, Ω_0=3, deflection amplification factor, C_d=5½, inherent damping, ξ_0=0.05, and SCWB (strong column/weak beam ratio)≥1.2. The parameters for concrete design were assumed as: f'_c=4000 psi, E_c=3.6x10^6 psi, and γ_c=0.0868 lb/in^3. The reinforcement steel was taken as grade A615 with f_y=69000 psi, and ε_y=0.002. Load combinations, including seismic effects, were adopted from ASCE-7.

The building was modeled as a tridimensional frame and subjected to the scaled earthquakes, THA were carried out in OpenSees [12] to obtain the average of the maximum responses, and the members were designed by capacity according with ACI-318.

In structural design, there is a large number of parametric combinations that could meet the strength and ductility requirements imposed by design specifications. In this study, the cross sections of the members were reduced although it resulted in higher, but allowable, ratios of reinforcement steel in order to obtain the most unfavorable scenario for sustainability as the emissions from reinforced steel are higher than those from plain concrete (Section 4).

The column's sizes, and the steel reinforcement ratios for flexure, ρ, and shear, ρ_s are presented in Table 1. Table 2 shows the results for beams including dimensions, steel reinforcement ratios for shear steel, ρ_s, and the steel ratios for the top, ρ_{top}, and bottom of the section, ρ_{bottom}. In all cases, the value ρ_s is the average calculated through the length of the member. The story drifts ratios are listed in Table 3. It can be observed that the design of frames was not significantly controlled by drift constraints but for strength requirements.

The SCWB ratios for all frames are shown in black font in Fig. 3. It can be observed that in the top floor, SCWB ratios in the three central frames are below the 1.2 threshold due the beams sizes adjacent to these joints. This *non-code-conforming* SCWB ratios was maintained due to: *a)* the conservatism in the column sizes on that level, and *b)* P-Δ effects were negligible as the stability coefficient, θ, defined in ASCE-7, did not exceed 0.1 for all the stories.

The average base shear obtained with time-history response analysis was V_{TH}=906 kips. The calculated equivalent static seismic base shear of the building was V_S^{BL}=1037 kips, 10% smaller than the shear obtained in [8] because the dead loads from nonstructural components were not considered in this study. The design satisfied the minimum base shear requirement for the baseline building, $V_{TH} \geq V_{min}^{BL} = 0.85V_S^{BL}$=881 kips.

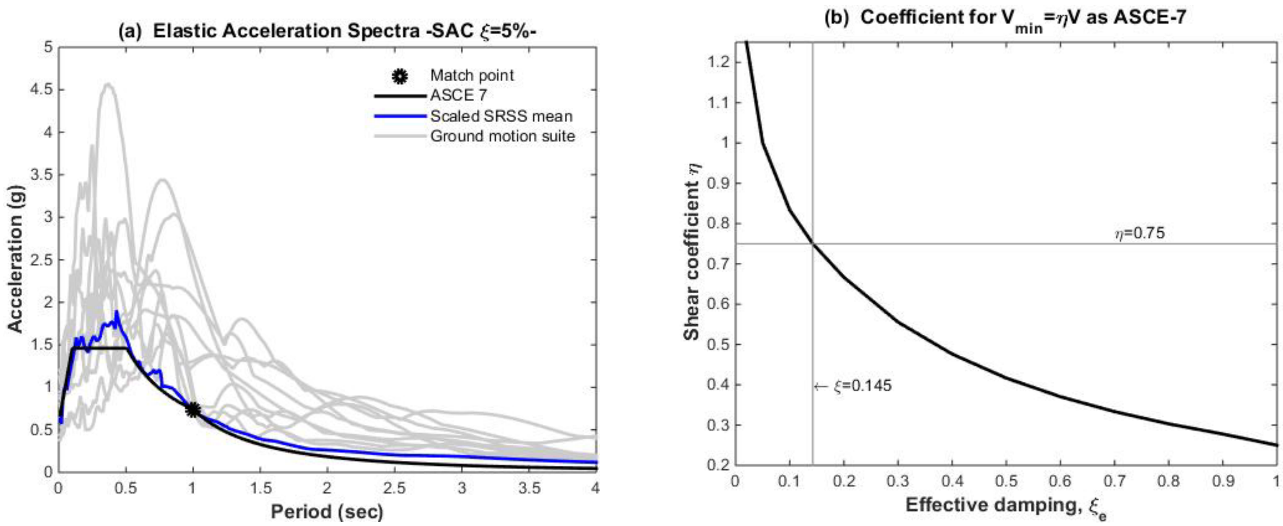

Fig. 2 – Acceleration spectra

3.3 Building with viscous dampers

In current major codes, two main considerations may appear for the design of buildings with supplemental dampers. The first is related to the force-resisting system, and the second to the amount of damping provided by supplemental devices, ξ_d. ASCE-7 requires the building to have in each lateral direction a seismic force-resisting system, as its bare counterpart, to resist a minimum base shear, V_{min}^{VD}. This implies that limited inelastic deformations are permitted to occur in the RC frames, according to a SCWB mechanism. Some codes may also limit the amount of the effective damping of the system, ξ_e, directly limiting ξ_d since ξ_0 is constant ($\xi_e=\xi_d+\xi_0$). ASCE-7 does not limit the amount of damping but specifies the minimum base shear in function of the amount of damping as $V_{min}^{VD}=\eta_d V_S^{VD}$ with $\eta_d \geq 0.75$, and V_S^{VD} equal to the equivalent static seismic base shear. Fig. 2(b) illustrates the variation of η_d with ξ_e derived from ASCE-7; it can be observed that even for high values of damping, $\xi_e \geq 0.144 \approx 0.15$, the minimum allowable coefficient for shear is η_d =0.75. Therefore, for $\xi_d \geq 0.10$ no additional reduction in the minimum base shear is obtained and thus, no extra reduction in structural sections may be achieved. For this reason, the viscous dampers were designed to provide a maximum value, ξ_d =0.10. However, it is worthwhile to mention that even with this consideration, there is still a large number of combinations for the sizes of columns and beams that would produce similar base shear forces, resulting in variations in the final amount of structural materials. In any case, the dispersion may not be significant since the design is focused on the reduction of the cross sections and the maximum reinforcement steel ratio acts as limiting parameter.

The source of supplemental damping is not explicitly mentioned in ASCE-7, several sources are permitted indeed. In this study, nonlinear viscous dampers represented by Maxwell model (α=0.2) were chosen as they do not significantly affect the dynamic characteristics of the building.

A design methodology derived from the research objectives was implemented as follows:

1. Similarly as in *Damage-controlled Design*, the whole structure was divided into two systems: *a)* The primary, consisting of the force-resisting system designed to withstand $V_{min}^{VD}=0.75V_S^{VD}$, and *b)* the secondary, consisting of supplemental dampers designed to provide $\xi_d=0.10$.
2. Configuration of eight dampers, *VD*, in each exterior frame, see Fig 4(a), and calculation of the damping coefficient, C_d, for each damper.
3. Performing nonlinear time-history analysis to calculate the average of the maximum responses.
4. Design of structural members by capacity and story drifts verification by THA.

The sections and reinforcement steel ratios for columns and beams are listed in Table 1 and Table 2, respectively. The SCWB ratios are shown in blue font in Fig. 3 (for SCWB<1.2 see Section 3.3). The primary system was designed to resist a base shear V_{min}^{VD}=523 kips. The calculated damping coefficients for the secondary system were: C=428 kips/in for VD-1, and C=285 kips/in for VD-2 for a total ξ_d=0.105. The drift ratios are presented in Table 3.

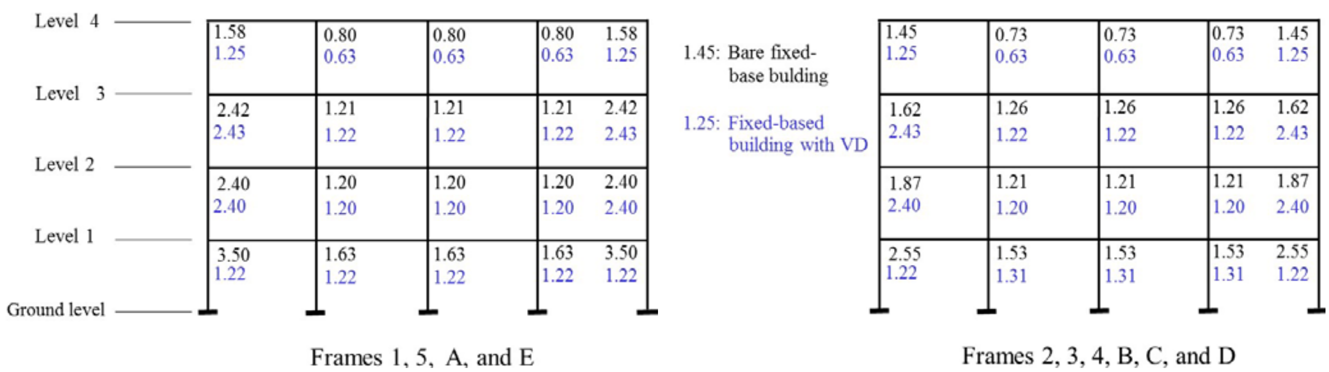

Fig. 3 – SCWB ratios

3.4 Base-isolated building

The objective of base isolation is to prevent structural damage by decoupling the structure from the damaging components of the earthquake. It also provides seismic energy dissipation thereby, reducing forces and displacements on the structure by as much as 50%. There are many types of isolators; the effectiveness of the device depends on several factors including the characteristics of the earthquake, and the properties of the structure among others. In this study, to obtain a significant reduction in structural sections, high damping rubber bearings (HDRB) were used.

The baseline building was assumed to have a single isolator under each individual column as Fig. 4(b) illustrates. A horizontal diaphragm consisting of slab and beams *B0* and *B0-A*, was included above the isolation interface (ground level) to provide continuity, and to transmit forces among the structural members at that level.

The performance objective was expressed by the elastic response of the superstructure. Its story drifts, θ_d, were limited by the allowable story drifts, θ_y, defined by the following semi-empirical equation [13]

$$\theta_y=0.5\varepsilon_y \cdot L_b/h_b \tag{1}$$

where L_b is the beam span, h_b is the overall beam depth, and ε_y is the yield strength of the flexural reinforcement. The complimentary parameters for design were taken as: response modification coefficient, R^{IS}=2, and deflection amplification factor, C_d^{IS}=2.

ASCE-7 specifies the minimum base shear to be resisted by the superstructure as $V_{min}^{IS}=\eta_d^{IS}V_S^{IS}$, with η_d^{IS}=0.6, and V_S^{VD} equal to the equivalent static seismic base shear. The period of the base-isolated building was set as $T_{IS}=2.5T$=2.5 sec.

A design methodology derived from the one proposed in [14] was implemented as follows:

1. Preliminary design of the superstructure to resist V_{min}^{IS}.
2. The whole structure was simplified as an equivalent SDOF system with equivalent properties, $M_{eq}=W/g$, $K_{eq}=K_{IS}=(2\pi/T_{IS})^2\cdot M_{eq}$, and $\xi_{eq}=\xi_{IS}=0.24$ (typical damping for a commercial HDRB).
3. With T_{eq} and ξ_{eq}, the performance objective was related to the maximum horizontal displacement, Δ_d, which did not exceed the maximum capacity of the isolators, Δ_{IS}.
4. Calculation of the spectral ordinate, S_a^{IS} with T_{eq} and ξ_{eq}. Calculation of $V_{IS}=S_a^{IS}\,W$, and comparison with V_{min}, the design of the superstructure was done with the greater value.
5. Perform nonlinear time-history analysis to calculate the average of the maximum responses.
6. Design of structural members by capacity and story drift verification by THA.

The resulting equivalent properties for each individual isolator were k_e=86.3 kips/ft, ξ_e=0.24, with vertical stiffness k_c=1.94e5 kips/ft, yield strength F_y=20.2 kips, and 10% of post-yield stiffness ratio. The superstructure was designed to resist the minimum base shear, V_{min}=695 kips. The final design of columns and beams is shown in Table 1 and Table 2, respectively. As Table 3 indicates, the most remarkable consequence of the reduction in seismic forces is the drastic reduction of the story drifts. It reveals the design was clearly governed by the capacity required to resist the minimum shear imposed.

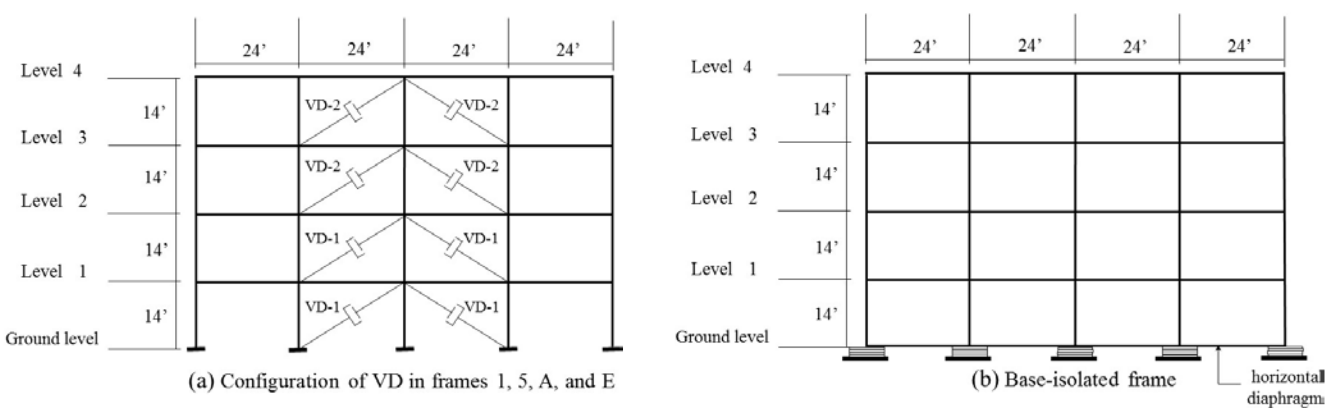

Fig. 4 – Configuration of seismic devices

4. Sustainable performance

4.1 General behavior

From a strictly sustainable point of view, an inventory of embodied emissions which consider the local and actual conditions of the production process should be used. This information, however, is not always available. For this reason, the ICE database shall be adopted as it is considered one of the most robust and transparent available inventories. It also accounts explicitly for steel reinforcement emissions; in RC steel is a significant design parameter as Tables 1 and 2 reveal. Additionally, it allows a straightforward calculation of the embodied emissions for RC manufactured with recycled materials. Although the coefficients from the database are significant parameters for this study, the three buildings shall be assessed with the same values; thus, no significant dispersion in the sustainability behavior is expected.

The coefficients for embodied energy and embodied carbon are shown in Table 4 (for a 4000/5000 psi concrete), in the original units reported in the ICE database.

The embodied emissions per unit of weight were calculated as the product of the coefficients, S_c, by the weight of the reinforced concrete, W_{RC}, of the structural members as

$$E_{E/C}=W_{RC}\cdot S_c \tag{2}$$

The calculations were divided in two parts. The first excluded the contribution in the total emissions of high amounts of reinforcement steel, equivalent to adopt general concrete coefficients. The second explicitly included the contribution of reinforcement steel into the total emissions, equivalent to adopt specific concrete coefficients. In this way, a reasonable evaluation of the sustainable behavior of highly reinforced members is performed, and the importance of using proper coefficients that account for emissions of all RC components is highlighted. In the assessment, no recycled contents into RC were assumed in order to consider the most unfavorable condition.

Figure 5 compares the emissions for the building with general concrete with the one analyzed using specific concrete. The EE is reported on BTU for consistency with the U.S customary units adopted in this study.

For the building with general concrete, the results reveal what it may be inferred from Eq. 2: the building with smaller emissions will be the lighter one as the sustainability coefficients are proportional to the weight; similarly, the heavier building will produce greater emissions. Fig. 5(a) clarifies it, the building with viscous dampers shows better sustainable performance with EE=981.4 BTU, and EC=355.6 kipsCO_2 against the baseline building with EE=1351 BTU and EC=489.6 kipsCO_2. The sustainable indicators of the base-isolated building, EE=1262 BTU and EC=457.2 kipsCO_2, did not improve significantly compared with the baseline building. It is worthwhile to note that embodied emissions of beams were greater than those from columns for all buildings. Although general concrete may be useful for preliminary analysis, it may produce unrealistic conclusions when high steel reinforcement ratios are prioritized like in the design described in Section 3. Sustainable indicators for reinforcement steel should be assessed separately.

For the building with specific concrete, the embodied energy and embodied carbon notably increase for all buildings as Fig. 5(b) depicts. It can be observed the emissions from columns were greater than those from beams. This is explained due to the conservatism in the column required to meet the minimum SCWB ratios in buildings with inelastic design. On the contrary, this behavior is not observed in the IS Building designed to keep elastic even with high reinforcement steel ratios. The quantitative assessment for this case is presented in Section 4.2.

The comparison of the embodied emissions from reinforcement steel is presented in Fig. 6. It can be observed the emissions from beams of the IS Building nearly match those of its Baseline building counterpart, except for B2-A and B3, and B3-A. The emissions from beams of Bulding+VD did not change significantly as it occurred in other buildings. For columns, there was not a very well defined pattern although in all cases, the emissions were smaller for Building+VD. In practicing engineering, it is common to homogenize the ratios of reinforcement steel through member's sections, based on costs or construction criteria; the results from Fig.6 suggest the sustainability impacts should also be considered on this decision.

Before the quantitative assessment of sustainability, it is worthwhile to note from Fig. 5 that the indicators of the IS Building are very close to those of the Baseline building. This is due to: *a)* the superstructure of the base-isolated building was designed to remain elastic, then no additional reduction in the design forces was applied and therefore no significant reduction in steel ratios was achieved, and *b)* the rigid diaphragm required above the isolation interface (Section 3.4) resulted in an additional floor system. In this case, the diaphragm itself contributed with 15% and 21% for total EE and EC, respectively. To complete the analysis, the embodied emissions from HDRB (not currently available) should be calculated and the whole sustainability assessed.

4.2 Sustainability Assessment

To calculate the sustainability improvement, I_m, the indicators EE and EC from buildings with seismic devices were normalized with those from the baseline building as

$$I_m=[1-(\text{EE or EC})_{\textit{proposed building}}/\ (\text{EE or EC})_{\textit{baseline building}}]\text{x}100 \tag{3}$$

Table 1 – Flexure reinforcement ratio of columns, ρ_c

		C1	**C1-A**	**C2**	**C2-A**	**C3**	**C3-A**	**C4**	**C4-A**
Baseline building Cols 30in x 30 in	ρ_c	0.042	0.035	0.035	0.035	0.031	0.016	0.02	0.016
	ρ_{cs}	0.0035	0.0030	0.0030	0.0025	0.0024	0.0020	0.0019	0.0016
Building + VD Cols 23in x 23 in	ρ_c	0.040	0.034	0.034	0.034	0.029	0.029	0.013	0.013
	ρ_{cs}	0.0056	0.0056	0.0047	0.0047	0.0038	0.0038	0.0029	0.0029
IS building Cols 26in x 26 in	ρ_c	0.050	0.035	0.035	0.025	0.027	0.013	0.020	0.011
	ρ_{cs}	0.0064	0.0060	0.0060	0.00055	0.0055	0.0050	0.0048	0.0040

Table 2 – Flexure reinforcement ratio of beams, ρ_b

		B0	**B0-A**	**B1**	**B1-A**	**B2**	**B2-A**	**B3**	**B3-A**	**B4**	**B4-A**
Baseline building	b [in]	–	–	18	18	18	18	18	18	18	18
	h [in]	–	–	32	32	32	32	30	30	30	30
	ρ_{top}	–	–	0.012	0.009	0.012	0.009	0.009	0.006	0.006	0.005
	ρ_{bottom}	–	–	0.009	0.007	0.01	0.007	0.007	0.004	0.004	0.004
	ρ_{bs}	–	–	0.0032	0.0025	0.0025	0.0020	0.0025	0.0018	0.0017	0.0012
Building + VD	b [in]	–	–	18	18	18	18	16	16	16	16
	h [in]	–	–	28	28	28	28	24	24	24	24
	ρ_{top}	–	–	0.007	0.007	0.006	0.006	0.007	0.007	0.004	0.004
	ρ_{bottom}	–	–	0.006	0.005	0.004	0.004	0.005	0.005	0.004	0.004
	ρ_{bs}	–	–	0.0027	0.0027	0.0022	0.0022	0.0016	0.0016	0.0014	0.0014
IS building	b [in]	18	18	18	18	18	18	16	16	16	16
	h [in]	30	30	28	28	28	28	24	24	24	24
	ρ_{top}	0.006	0.006	0.015	0.013	0.015	0.013	0.015	0.013	0.008	0.006
	ρ_{bottom}	0.004	0.004	0.012	0.011	0.012	0.011	0.012	0.011	0.005	0.004
	ρ_{bs}	0.0016	0.0018	0.0027	0.0027	0.0024	0.0024	0.0022	0.0022	0.0022	0.0022

Table 3 – Story drifts [%]

	Bare building		**Building + VD**		**IS building**	
Story	Calculated	Allowable	Calculated	Allowable	Calculated	Allowable
4	0.6	2.0	0.4	2.0	0.1	1.2
3	1.2	2.0	0.7	2.0	0.1	1.2
2	1.1	2.0	0.9	2.0	0.1	1.0
1	1.0	2.0	0.8	2.0	0.1	1.0

Table 4 – Sustainability coefficients, S_c

EE [MJ/kg]	EC [kgCO_2/kg]	*for each 100 kg of reinforcement steel per m^3 of concrete In this study, for general concrete the terms 1.04 and 0.077 were multiplied by 0
0.95+1.04*	0.148+0.077*	

The results for the most realistic building (specific concrete) are summarized in Table 5. It can be observed the most significant improvement is in the building with viscous dampers. It is actually, the only one that simultaneously meets the requirements of performance-based design and shows improvements on predefined sustainability indicators, EE and EC. Thus, Building+VD satisfied the proposed definition of sustainable structural design. For the base-isolated building, no improvement is achieved in EE and a very small improvement is obtained for EC. This building did not satisfy the requirements of sustainable structural design for both indicators, only for EC.

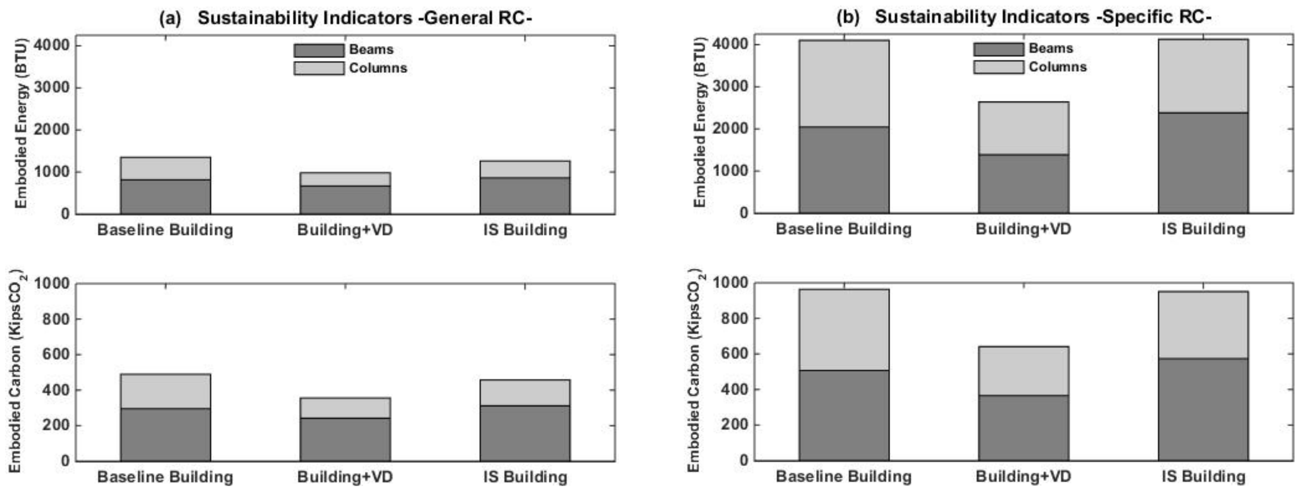

Fig. 5 – Sustainability Indicators

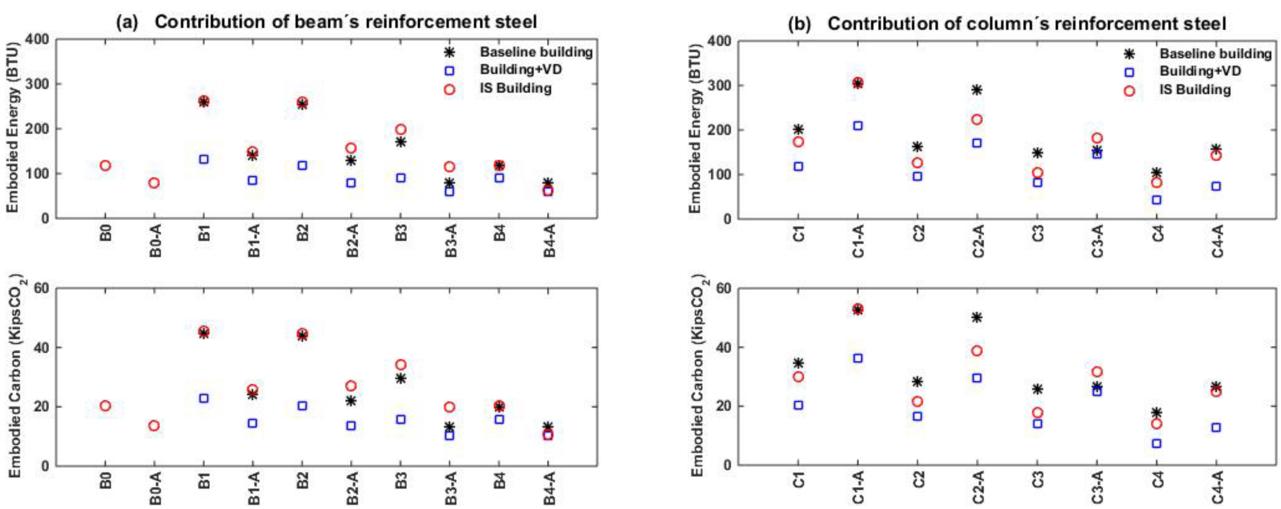

Fig. 6 – Embodied emissions of reinforcement steel by sections

Table 5 – Sustainability Improvements, I_m

	Baseline building	Building+VD			IS building		
	Calculated	Calculated	Normalized	I_m	Calculated	Normalized	I_m
EE [BTU]	4100.7	2639.7	0.644	35.6%	4126.9	1.006	-
EC [$KipsCO_2$]	963.1	641.2	0.665	33.5%	950.6	0.987	1.3%

The very small difference in the normalized values of sustainability indicators, suggest the coefficients for EE and EC are highly correlated. This is typical when the energy required in the material production mainly comes from sources of carbon emissions.

Although the building with supplemental damping showed the best sustainable performance, the contribution of viscous dampers into the total embodied emissions is still pending. After an extensive research, no reliable information of embodied emission for viscous dampers was found from manufacturers. However, even without these data, the results suggest there is a wide interval of sustainability indicators to allocate seismic devices within the definition of sustainable structural design. For example, if the target improvement of embodied carbon is set to 10%, each individual damper should have a “cradle-to-gate” coefficient equal to EC_{VD}=[0.90(963.1 KipsCO_2) - 641.2 KipsCO_2]/32=7.05 KipsCO_2 (assuming the same EC for all dampers). Moreover, the interval to allocate dampers may become wider by using recycled contents in either, reinforcement steel or plane concrete.

5. Discussion and conclusions

This study investigated the effectiveness of seismic control devices in reducing initial embodied emissions of RC building’s superstructures within the context of sustainable structural design. It was defined as the pattern that holistically satisfies a robust earthquake-resistant framework, and simultaneously demonstrates improvements on predefined sustainability indicator(s) against a baseline structure. The embodied energy and embodied carbon were adopted as sustainable indicators; their values per unit volume of concrete (coefficients) were taken from an existing database.

The methodology presented is flexible enough to straightforwardly implement coefficients for EE and EC from a different database. It also allows the direct evaluation of the sustainable contribution of each individual structural member, and the contribution of the separate components of reinforced concrete, namely, steel and plain concrete. Besides, it is faster and more practical approach than the full Life Cycle Assessment. Moreover, no further knowledge and tools are required for its implementation. It could be also be convenient for LEED® analysis; sustainable structural design may be performed as shown in this study and taken as input in complex integrative models required for LEED® certification.

The embodied emissions from a base-isolated building (HDRB+elastic superestructure), and one equipped with supplemental dampers (viscous damping+hysteretic dissipation) were normalized with those from a conventionally-designed baseline building (hysteretic dissipation). For the buildings with seismic devices, the dimensions of the structural members were reduced increasing the steel reinforcement ratios, their maximum code allowable were set as limiting values. In actual cases, additional parametric combinations should be evaluated according to the performance objectives and the global sustainability behavior expected throughout the life cycle of the building.

It was found that only the building equipped with viscous dampers showed sustainability improvements. Superstructures designed to remain elastic during severe earthquakes may not necessarily be sustainable designed, especially base-isolated buildings having extra embodied emissions from the rigid diaphragm above the isolation interface. The results suggest the use of two simultaneous ways of seismic energy dissipation is an efficient approach to achieve sustainable structural design. In current practicing engineering, it may be obtained by: *a)* inelastic superstructure (hysteretic dissipation) with supplemental damping (viscous or hysteretic), and *b)* base isolation (hysteretic and/or supplemental damping) with inelastic superstructure (hysteretic dissipation).

This study was conducted with a high level of uncertainty about the embodied energy and embodied carbon of viscous dampers and rubber bearings. As the author knowledge, the embodied emissions from seismic devices have not yet been made public from manufacturers so they were not included in the analysis. However, the results suggest there is a wide interval to allocate them, without affectation in the sustainability improvements achieved. To extend this interval, recycled contents on the components of reinforced concrete may be included as an effective strategy. Additional analysis considering the emissions of seismic devices throughout their life cycle are needed before final conclusions can be draw.

One major factor that greatly influences the results concerns the emission's coefficients used in the analysis. It is recommended the use of robust and transparent inventories that realistically approximate the manufacturing conditions of the actual construction materials.

It was also observed the sustainability improvements depend on the indicators chosen (e.g. EE or EC). A careful selection of the sustainability indicators considering their degree of correlation should be performed to simulate the actual or most unfavorable case.

Sustainable-oriented reduction of structural sections involves several factors beyond appropriate size and efficient work of structural elements. The safety requirements imposed by design regulations must be satisfied. Thus, further multidisciplinary research to assess the contribution of additional parameters, and to study different approaches to achieve sustainability will be the focus of future investigations.

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7. References

[1] Dokka T H, Sartori I, Thyholt M, Lien K, Lindberg K B (2013): "A Norwegian Zero Emission Building Definition". *Proceedings from Passivhus Norden*. 15-17 October. Göteborg, Sweden.

[2] USGBC (2014): "LEED® Core Concepts Guide: An Introduction to LEED and Green Building", 3rd Ed., April

[3] BREE Global (2016): "BREEAM International New Construction 2016". Technical Manual. Version: SD233

[4] Deru M, Torcellini P (2004): "Improving Sustainability of Buildings through a Performance-Based Design Approach: Preprint". United States. Retrieved from http://www.osti.gov/scitech/servlets/purl/15009461

[5] ISO (2011): ISO 14040. "Environmental management, Life cycle assessment, principles and framework". *International Organization for Standardization*. Geneva, Switzerland.

[6] Kawai K, Sugiyama T, Kobayashi K, Sano S (2005): "Inventory data and case studies for environmental performance evaluation of concrete structure construction", *Journal of Advanced Concrete Technology*, Japan Concrete Institute, **3**(3), 435-456

[7] Hammond G P, Jones C I (2011): *Inventory of (Embodied) Carbon & Energy (ICE)*, Department of Mechanical Engineering. University of Bath.

[8] Lashgari M (2014): "Comparative study of base-isolated and fixed-based buildings using a damage/cost approach". *Construction Systems - Dissertations & Theses*. Paper 16. University of Nebraska-Lincoln.

[9] ASCE (2010): "Minimum design loads for buildings and other structures". Standard ASCE/SEI 7-10, Reston Virginia, USA.

[10] ACI (2014): "Building Code Requirements for Structural Concrete and Commentary", ACI committee 318-14, American Concrete Institute, Farmington Hills, USA.

[11] Shome N, Cornell A C (1998): "Normalization and Scaling Accelerograms for Nonlinear Structural Analysis", *Proceedings of the 6th U.S. National Conference on Earthquake Engineering*. Paper 243. Seattle, Washington

[12] OpenSees, (2006): Open System for Earthquake Engineering Simulation. *Pacific Earthquake Engineering Research Center*. Univ. of California, Berkeley.

[13] Priestley M J N, Calvi G M, Kowalski M J (2007): *Displacement-based seismic design of structures*, IUSS Press, Pavia, Italy.

[14] Sanchez-Flores F, Igarashi A (2012): "Displacement-based seismic design of base-isolated bridges with viscous dampers". *Proceedings of the XV World Conference on Earthquake Engineering*. Paper 0911, Lisbon. Portugal.