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# ON THE PERFORMANCE OF A STRUCTURAL ANALYSIS COST REDUCTION TECHNIQUE WHEN APPLIED TO RESIDENTIAL BUILDINGS

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**Abstract.** *Time integration is a versatile tool in structural dynamic analysis, suffering from considerable computational cost and inexactness in responses. For the special case of analysis against digitized excitations, recently a technique is proposed for integration with steps larger than the steps of excitation, and is successfully implemented in several practical analyses. In view of the social and financial importance of residential buildings, with five to twenty floors, in this paper, the performance of the recent technique regarding the structural systems of these buildings is examined and specifically it is demonstrated that even with no a priori knowledge about the structure and response, and independent of the analysis method, we can halve the computational cost in the price of trivial loss of accuracy.*

## 1 INTRODUCTION

Earthquakes are of the most potentially destructive phenomena. Despite the considerable progress, in anti-seismic analysis and design, there exist ambiguities in reliable protection against earthquakes, specially, for the current complicated architectural and structural designs. Considering this, besides the stochastic nature of strong ground motions, a main stage in advanced anti-seismic design is time history analysis against several appropriately selected earthquake records, somehow putting the effects together, and controlling, the adequacy of the resulting structural behavior. Direct time integration is the most versatile tool for time history analysis [1, 2], according to which, after discretization in space [3-5], and arriving at

$$\mathbf{M}\ddot{\mathbf{u}}(t)+\mathbf{f}_{\mathbf{int}}(t)=\mathbf{f}(t) \qquad 0\le t<t_{\text{end}}$$
$$\text{Initial Conditions:}\ \left|\begin{array}{l}\mathbf{u}(t=t_0)=\mathbf{u}_0\\ \dot{\mathbf{u}}(t=t_0)=\dot{\mathbf{u}}_0\\ \mathbf{f}_{\text{int}}(t=t_0)=\mathbf{f}_{\text{int}_0}\end{array}\right. \qquad (1)$$
$$\text{Restraining conditions: }\mathbf{Q}$$

($t$ and $t_{\text{end}}$ imply the time and the duration of the dynamic behavior; $\mathbf{M}$ is the mass matrix; $\mathbf{f}_{\text{int}}$ and $\mathbf{f}(t)$ stand for the vectors of internal force and excitation; $\mathbf{u}$(t), $\dot{\mathbf{u}}$(t), and $\ddot{\mathbf{u}}$(t) denote the vectors of displacement, velocity, and acceleration; $\mathbf{u}_0$, $\dot{\mathbf{u}}_0$ and $\mathbf{f}_{\text{int}_0}$ define the initial status of the model; also see [6]; and, $\mathbf{Q}$ represents some restricting conditions, e.g. additional constraints in problems involved in impact or elastic–plastic behavior [7, 8]), Eqs. (1) need to be analyzed for several strong ground motion (several $\mathbf{f}(t)$) [9-11].

Time integration analyses are not only versatile, but also simple. However, the price is inexactness and computational expensiveness. The most important parameter to control the inexactness and computational cost, also acting as the algorithmic parameter [12], of time integration, is the integration step size, $\Delta t$ [13]; in seismic analyses, generally constant throughout the integration [1, 14]. Because of this significance and the fact that the effect of $\Delta t$ on the inexactness and computational cost is adverse, assigning an appropriate value to $\Delta t$ plays an important role in the efficiency and adequacy of integration and time history analyses. A current comment in this regard is as noted below [14-16]:

$$\begin{array}{ll}\Delta t=\text{Min }(\frac{T}{10},\ {}_s\Delta t,\ {}_f\Delta t) & \text{for linear systems}\\ \Delta t=\text{Min }(\frac{T}{100},\ {}_s\Delta t,\ {}_f\Delta t) & \text{for nonlinear systems}\end{array} \qquad (2)$$

where, $T$ is the smallest dominant period of the response, ${}_s\Delta t$ is the maximum step size, providing numerical stability for linear analyses, and ${}_f\Delta t$ is the step size, by which, the earthquake record is digitized.

Recently, based on the basic essentiality of numerical computations, i.e. convergence [17, 18], a technique is proposed, for reducing the effect of ${}_f\Delta t$, in Eqs. (2), such that the analyses can be carried out with considerably less computational cost, with practically unchanged accuracy [19]; several theoretical studies and numerical investigations are carried out regarding the technique [19-31], successfully. In continuation, in this study, attention is paid to the social and practical importance of low to mid-rise residential buildings, and the performance of the technique in time integration analysis of thirty five- to twenty-story buildings (with different structural systems and geometries) are studied in detail. In Section 2, the structural systems, the excitations, and the analyses details are set. In Section 3, the outcome of the analyses, once, when implementing the technique, and once, when not implementing the technique, are compared. In Section 4, the observations are discussed, and finally, with a brief set of the achievements, the paper is concluded, in Section 5.

## 2 The structures of thirty residential buildings

Consider buildings with five, ten, fifteen, and twenty floors, two identical horizontal axes of symmetry, the geometries addressed in Table 1 (only the cases in a vertical column are considered together in a building), and the three structural systems: (a) lateral resistance by moment resisting frames, (b) lateral resistance by bracings, and (c) lateral resistance by moment resisting frame and bracings (cases (a) and (b) are not considered for buildings with twenty floors [11]; for the bracings configuration, see Figure 1 [32]). In view of the selections, stated in Table 2, the structural systems are designed, according to the Iranian codes [11, 33], considering their linear behaviors, when subjected to two two-component strong motions selected in consistence with the design codes (see Figure 2).

| | | | |
|---|---|---|---|
| Number of bays | 4 | 5 | 6 |
| Length of bays (m) | 4 | 5 | 6 |

Table 1: Variety of geometry of the thirty buildings in horizontal plans, similar for building with different number of floors.

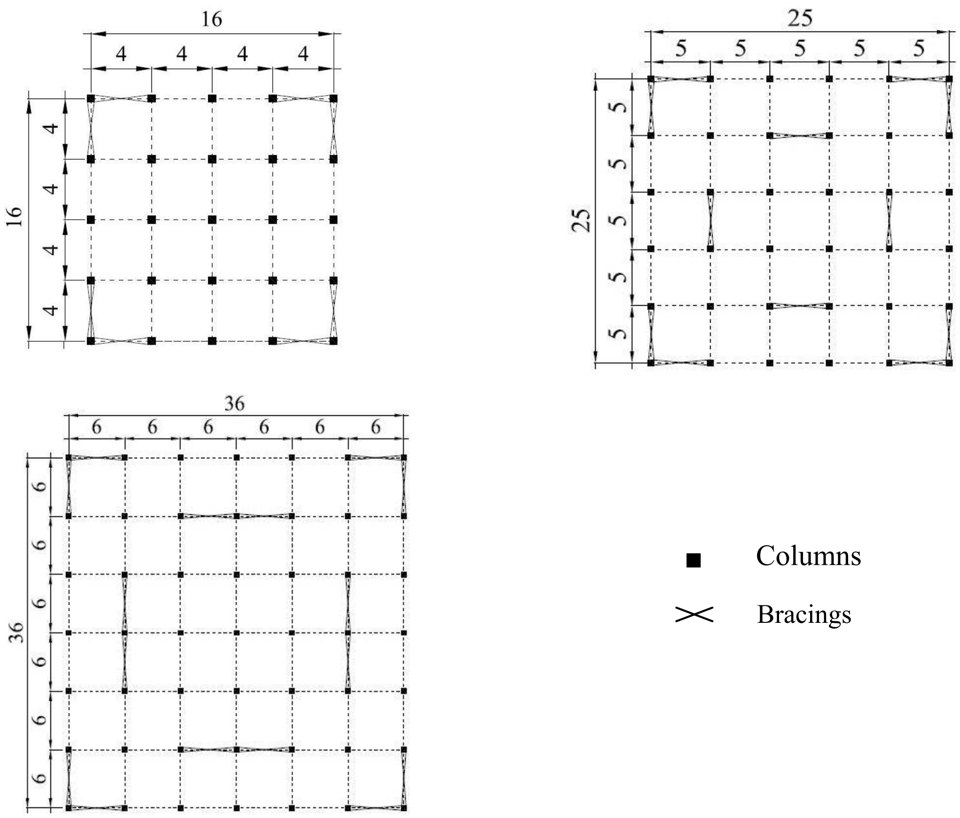


Figure1: Configuration of the bracings: (a) buildings with four bays in each horizontal direction, (b) buildings with five bays in each horizontal direction, (c) buildings with six bays in each horizontal direction [31].

| | |
|---|---|
| Material | Steel ST-37 |
| Occupancy | Residential |
| Importance Factor | 1 |
| Seismic Zone | 0.35 |
| Soil type | II ( $375\ \text{m/s} \leq Vs \leq 750\ \text{m/s}$ ) [11] |
| Floor height | 3 meters |

Table 2: Main details of the structural design.

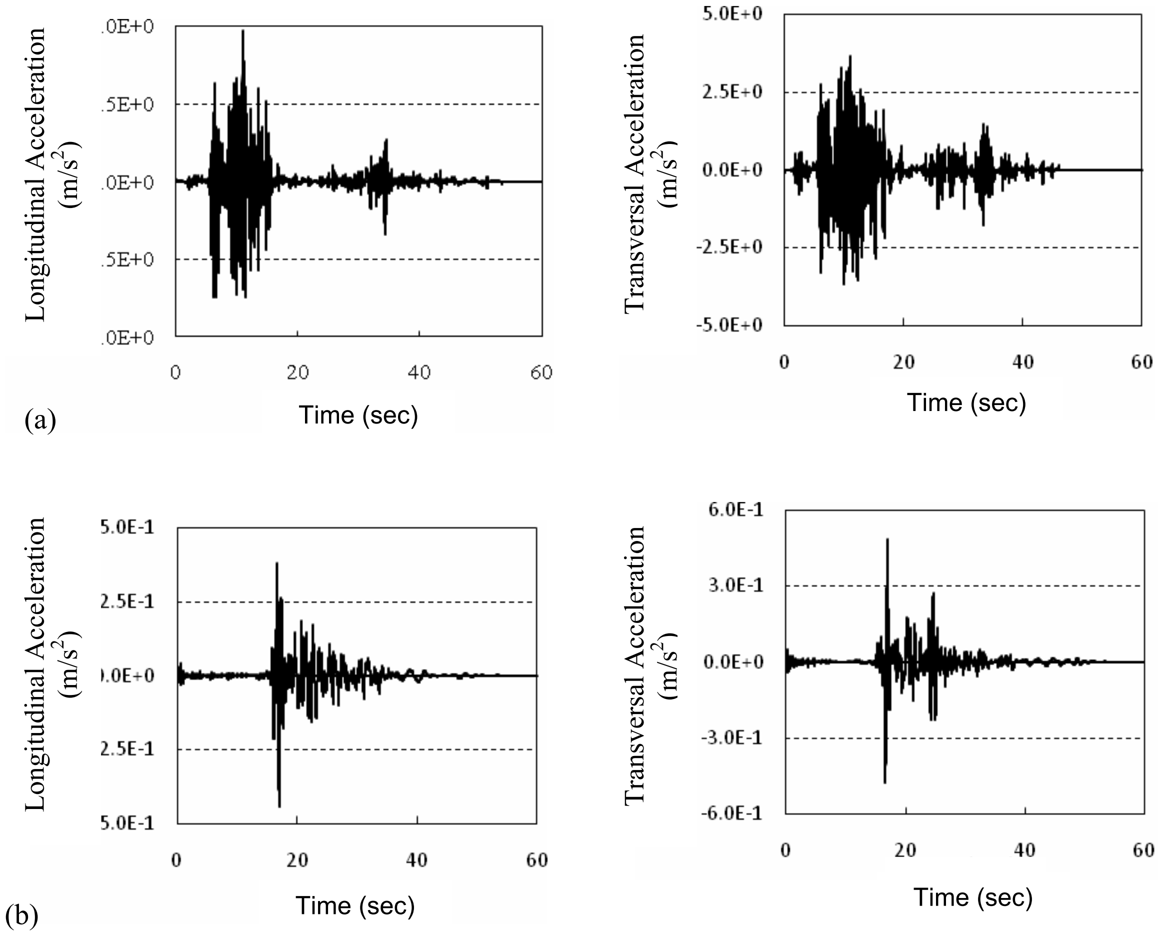


Figure 2: Strong ground motion arbitrarily selected in consistence with the anti-seismic code [11]:
(a) record 1 (b) record 2.

Top displacement and base shears are considered as the responses under interest and the average acceleration method of Newmark [1, 14, 34] is set as the integration method. For implementation of the recent technique, the value of $T$ is obtained from the issue 6-3-13 in [11], based on which, and Eq. (2), the parameter of the technique, $n$, is selected satisfying

$$n\ {}_{f}\Delta t \leq \Delta t \qquad n \in Z^{+} - \{1\} \tag{3}$$

Besides, for the sake of completeness and, in view of Figure 3, the case

$$n = 2 \tag{4}$$

is also numerically studied (see Figure (3).

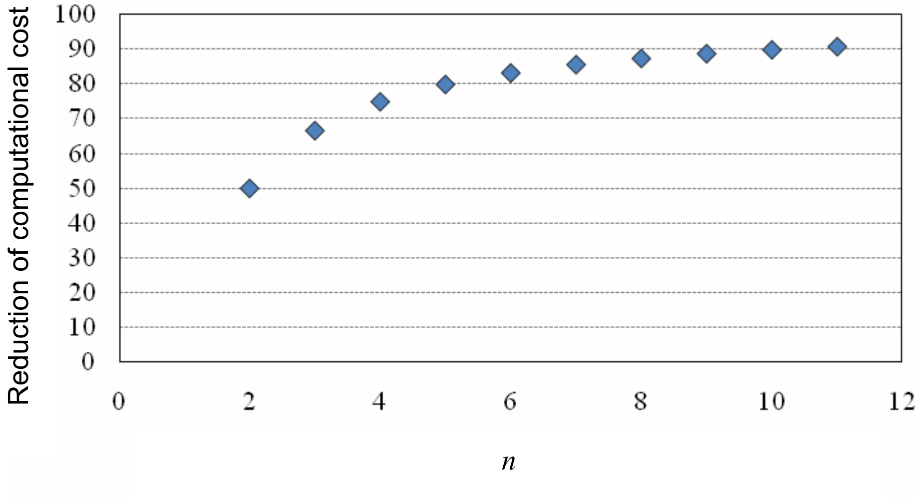


Figure 5: Reduction of computational cost for different values of *n*.

## 3 Numerical results

In this section, the results obtained for the ten-story building with dual system (structural system (c) introduced in the previous section) and five five-meter bays in each horizontal direction is pictorially reported, first; see Figures 4 and 5. Then, the detailed results of the thirty buildings are stated in Table 3-6. In view of the fact that the reduction of computational cost corresponding to each row of Tables 3-6 is at least 50% (see Figure 3), and that Tables 3-6 report deviations from conventionally obtained responses, not the corresponding errors, and finally, that the numerical values, in these tables, specifically those in correspondence to $n = 2$, are practically considerably small, the reported observation reveals the good performance of the recent cost reduction technique regarding residential buildings.

## 4 Discussion

The reported approximations of the results indeed imply a combination of the adequate performance of the recent technique and the good approximation obtained for $T$ from the anti-seismic code [11] (the latter can explain the few larger deviations in Tables 3-6). Regarding the latter, exceptional are the results corresponding to $n = 2$ (see the last columns in Tables 3-6), where, $n$ is not computed based on Eqs. (2) and (3). The results obtained in the case $n = 2$ address 50% reduction of computational cost, with trivial loss of accuracy, as a clear evidence for the adequate practical performance of the recent technique regarding different cases of low to mid-rise buildings structures with different systems and planar geometries. The performance can be explained, in view of [1, 13, 35], according to which

$$_{f}\Delta t < 0.02 \text{ sec} \tag{5}$$

for many earthquake and the fact that considering the existing engineering experiences, for the responses of mid-rise buildings, the least dominant period, $T$, satisfies

$$_{f}\Delta t < 0.02 \text{ sec} \tag{6}$$

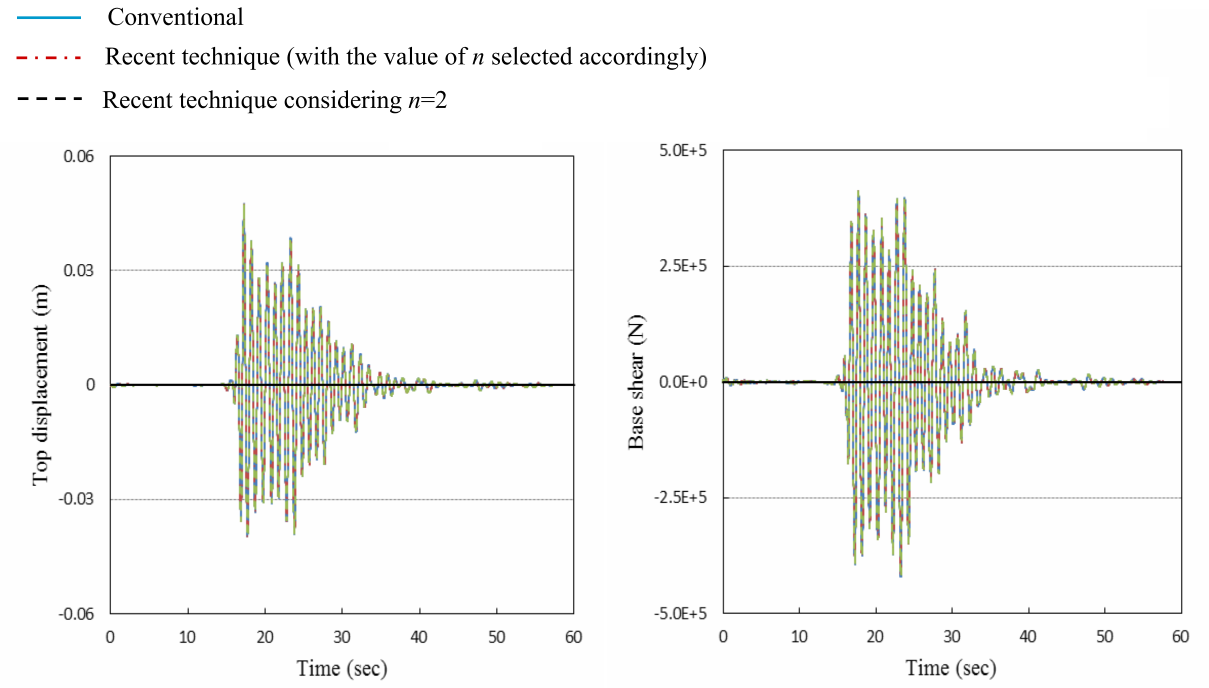


Figure 4: Response history for the ten-story building with dual structural system and five five-meter bays in each horizontal direction when the excitation is as noted in Figure 2(a): (a) top displacement, (b) base shear.

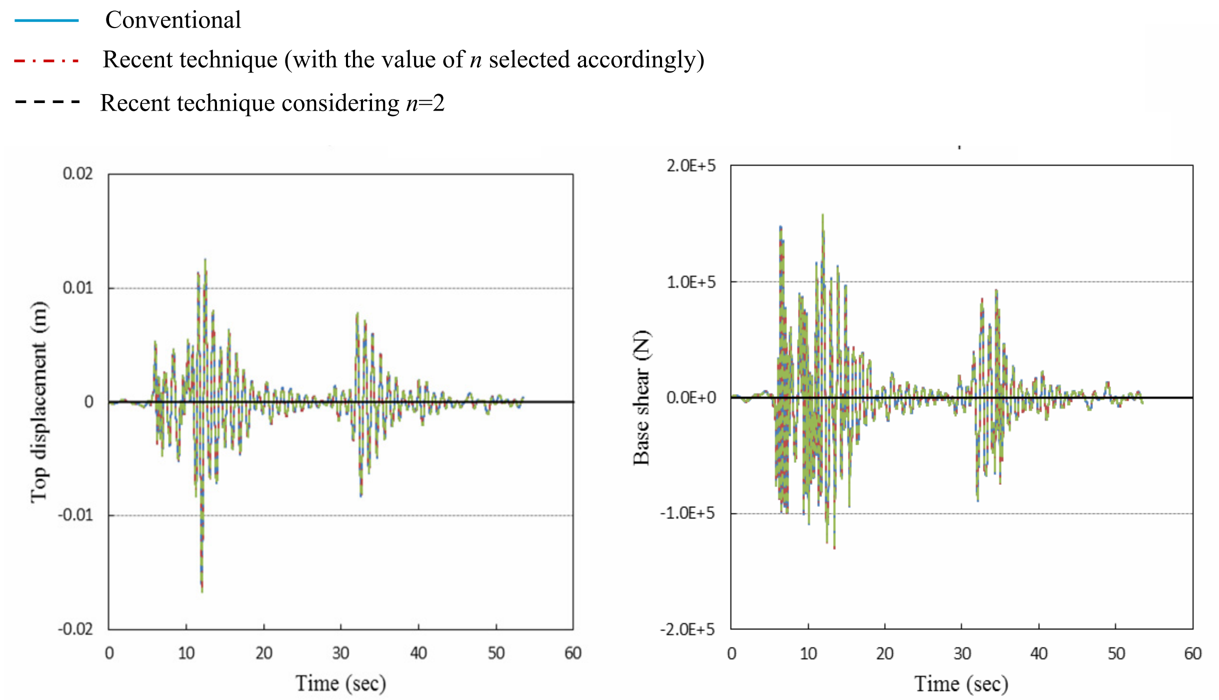


Figure 5: Response history for the ten-story building with dual structural system and five five-meter bays in each horizontal direction when the excitation is as noted in Figure 2(b): (a) top displacement, (b) base shear.

| Buildings structural system and geometry in plan | Recent technique with $n$ set according | Recent technique with $n$=2 |
|---|---|---|
| Five floors, four four-meters bays, and structural system (a) | 26.53 | 0.181 |
| Ten floors, four four-meters bays, and structural system (a) | 17.81 | 0.132 |
| Fifteen floors, four four-meters bays, and structural system (a) | 10.29 | 0.062 |
| Five floors, four four-meters bays, and structural system (b) | 0.569 | 0.324 |
| Ten floors, four four-meters bays, and structural system (b) | 0.622 | 0.114 |
| Fifteen floors, four four-meters bays, and structural system (b) | 2.480 | 0.111 |
| Five floors, four four-meters bays, and structural system (c) | 0.620 | 0.310 |
| Ten floors, four four-meters bays, and structural system (c) | 0.358 | 0.119 |
| Fifteen floors, four four-meters bays, and structural system (c) | 2.660 | 0.153 |
| Twenty floors, four four-meters bays, and structural system (c) | 3.470 | 0.070 |
| Five floors, five five-meters bays, and structural system (a) | 25.93 | 0.177 |
| Ten floors, five five-meters bays, and structural system (a) | 16.75 | 0.124 |
| Fifteen floors, five five-meters bays, and structural system (a) | 9.950 | 0.062 |
| Five floors, five five-meters bays, and structural system (b) | 0.650 | 0.390 |
| Ten floors, five five-meters bays, and structural system (b) | 0.645 | 0.176 |
| Fifteen floors, five five-meters bays, and structural system (b) | 2.750 | 0.119 |
| Five floors, five five-meters bays, and structural system (c) | 0.610 | 0.305 |
| Ten floors, five five-meters bays, and structural system (c) | 0.360 | 0.120 |
| Fifteen floors, five five-meters bays, and structural system (c) | 2.580 | 0.109 |
| Twenty floors, five five-meters bays, and structural system (c) | 4.680 | 0.090 |
| Five floors, six six-meters bays, and structural system (a) | 28.84 | 0.199 |
| Ten floors, six six-meters bays, and structural system (a) | 13.30 | 0.103 |
| Fifteen floors, six six-meters bays, and structural system (a) | 10.62 | 0.061 |
| Five floors, six six-meters bays, and structural system (b) | 0.636 | 0.380 |
| Ten floors, six six-meters bays, and structural system (b) | 0.340 | 0.154 |
| Fifteen floors, six six-meters bays, and structural system (b) | 2.540 | 0.096 |
| Five floors, six six-meters bays, and structural system (c) | 0.608 | 0.304 |
| Ten floors, six six-meters bays, and structural system (c) | 0.351 | 0.117 |
| Fifteen floors, six six-meters bays, and structural system (c) | 0.660 | 0.120 |
| Twenty floors, six six-meters bays, and structural system (c) | 4.680 | 0.096 |

Table 3: Deviation from the conventionally computed top displacements in terms of the $\mathbf{L}_\infty$ norm (%), when the excitation is as noted in Figure 2(a).

from which

$$\frac{T}{10_f\,\Delta t} \cong 2 = n \tag{7}$$

can be obtained in agreement with Eq. (4).

## 5 Conclusion

The performance of a recent technique for more efficient seismic analyses [18] is studied when implemented in time integration analysis of thirty six residential buildings designed according to seismic codes [11, 33], and the observations are theoretically explained. In conclusion, the parameter of the technique, $n$, can be set, with attention to the least dominant period approximately obtained from the anti-seismic code [11], leading to appropriate results regardless of the structures. Nevertheless, it is more practical, to upper bound the cost reduction to 50%, and with no *a priori* knowledge about the excitation or structural system, arrive at responses, in trivial deviation from the conventionally computed responses.

| Buildings structural system and geometry in plan | Recent technique with *n* set accordingly | Recent technique with *n*=2 |
|---|---|---|
| Five floors, four four-meters bays, and structural system (a) | 25.45 | 0.738 |
| Ten floors, four four-meters bays, and structural system (a) | 19.09 | 0.410 |
| Fifteen floors, four four-meters bays, and structural system (a) | 9.400 | 0.430 |
| Five floors, four four-meters bays, and structural system (b) | 1.610 | 0.939 |
| Ten floors, four four-meters bays, and structural system (b) | 1.120 | 1.610 |
| Fifteen floors, four four-meters bays, and structural system (b) | 6.590 | 1.250 |
| Five floors, four four-meters bays, and structural system (c) | 1.820 | 0.979 |
| Ten floors, four four-meters bays, and structural system (c) | 2.070 | 1.200 |
| Fifteen floors, four four-meters bays, and structural system (c) | 7.600 | 1.260 |
| Twenty floors, four four-meters bays, and structural system (c) | 4.760 | 0.574 |
| Five floors, five five-meters bays, and structural system (a) | 25.29 | 0.695 |
| Ten floors, five five-meters bays, and structural system (a) | 21.72 | 0.938 |
| Fifteen floors, five five-meters bays, and structural system (a) | 9.280 | 0.466 |
| Five floors, five five-meters bays, and structural system (b) | 1.390 | 0.783 |
| Ten floors, five five-meters bays, and structural system (b) | 2.360 | 1.330 |
| Fifteen floors, five five-meters bays, and structural system (b) | 2.960 | 1.110 |
| Five floors, five five-meters bays, and structural system (c) | 1.540 | 0.831 |
| Ten floors, five five-meters bays, and structural system (c) | 1.980 | 1.160 |
| Fifteen floors, five five-meters bays, and structural system (c) | 8.290 | 1.500 |
| Twenty floors, five five-meters bays, and structural system (c) | 5.370 | 0.640 |
| Five floors, six six-meters bays, and structural system (a) | 28.55 | 0.988 |
| Ten floors, six six-meters bays, and structural system (a) | 13.35 | 0.621 |
| Fifteen floors, six six-meters bays, and structural system (a) | 9.100 | 0.618 |
| Five floors, six six-meters bays, and structural system (b) | 1.750 | 0.925 |
| Ten floors, six six-meters bays, and structural system (b) | 1.890 | 0.696 |
| Fifteen floors, six six-meters bays, and structural system (b) | 6.050 | 0.970 |
| Five floors, six six-meters bays, and structural system (c) | 1.640 | 0.914 |
| Ten floors, six six-meters bays, and structural system (c) | 1.440 | 0.875 |
| Fifteen floors, six six-meters bays, and structural system (c) | 3.280 | 1.410 |
| Twenty floors, six six-meters bays, and structural system (c) | 5.370 | 0.640 |

Table 4: Deviation from the conventionally computed base shears in terms of the $\mathbf{L}_\infty$ norm (%), when the excitation is as noted in Figure 2(a).

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| Buildings structural system and geometry in plan | Recent technique with $n$ set accordingly | Recent technique with $n$=2 |
|---|---|---|
| Five floors, four four-meters bays, and structural system (a) | 1.040 | 0.089 |
| Ten floors, four four-meters bays, and structural system (a) | 0.396 | 0.054 |
| Fifteen floors, four four-meters bays, and structural system (a) | 0.515 | 0.064 |
| Five floors, four four-meters bays, and structural system (b) | 0.264 | 0.132 |
| Ten floors, four four-meters bays, and structural system (b) | 0.134 | 0.095 |
| Fifteen floors, four four-meters bays, and structural system (b) | 0.282 | 0.062 |
| Five floors, four four-meters bays, and structural system (c) | 0.303 | 0.182 |
| Ten floors, four four-meters bays, and structural system (c) | 0.144 | 0.082 |
| Fifteen floors, four four-meters bays, and structural system (c) | 0.249 | 0.049 |
| Twenty floors, four four-meters bays, and structural system (c) | 0.360 | 0.060 |
| Five floors, five five-meters bays, and structural system (a) | 1.010 | 0.089 |
| Ten floors, five five-meters bays, and structural system (a) | 0.613 | 0.042 |
| Fifteen floors, five five-meters bays, and structural system (a) | 0.541 | 0.051 |
| Five floors, five five-meters bays, and structural system (b) | 0.240 | 0.089 |
| Ten floors, five five-meters bays, and structural system (b) | 0.135 | 0.960 |
| Fifteen floors, five five-meters bays, and structural system (b) | 0.250 | 0.044 |
| Five floors, five five-meters bays, and structural system (c) | 0.240 | 0.180 |
| Ten floors, five five-meters bays, and structural system (c) | 0.147 | 0.084 |
| Fifteen floors, five five-meters bays, and structural system (c) | 0.281 | 0.052 |
| Twenty floors, five five-meters bays, and structural system (c) | 0.305 | 0.043 |
| Five floors, six six-meters bays, and structural system (a) | 0.971 | 0.083 |
| Ten floors, six six-meters bays, and structural system (a) | 0.501 | 0.055 |
| Fifteen floors, six six-meters bays, and structural system (a) | 0.548 | 0.069 |
| Five floors, six six-meters bays, and structural system (b) | 0.291 | 0.174 |
| Ten floors, six six-meters bays, and structural system (b) | 0.137 | 0.106 |
| Fifteen floors, six six-meters bays, and structural system (b) | 0.351 | 0.055 |
| Five floors, six six-meters bays, and structural system (c) | 0.265 | 0.199 |
| Ten floors, six six-meters bays, and structural system (c) | 0.168 | 0.105 |
| Fifteen floors, six six-meters bays, and structural system (c) | 0.283 | 0.070 |
| Twenty floors, six six-meters bays, and structural system (c) | 0.300 | 0.043 |

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| Buildings structural system and geometry in plan | Recent technique with $n$ set accordingly | Recent technique with $n$=2 |
|---|---|---|
| Five floors, four four-meters bays, and structural system (a) | 1.060 | 0.096 |
| Ten floors, four four-meters bays, and structural system (a) | 1.070 | 0.079 |
| Fifteen floors, four four-meters bays, and structural system (a) | 2.550 | 0.120 |
| Five floors, four four-meters bays, and structural system (b) | 0.329 | 0.176 |
| Ten floors, four four-meters bays, and structural system (b) | 0.199 | 0.109 |
| Fifteen floors, four four-meters bays, and structural system (b) | 0.855 | 0.154 |
| Five floors, four four-meters bays, and structural system (c) | 0.328 | 0.199 |
| Ten floors, four four-meters bays, and structural system (c) | 0.197 | 0.120 |
| Fifteen floors, four four-meters bays, and structural system (c) | 0.600 | 0.112 |
| Twenty floors, four four-meters bays, and structural system (c) | 0.920 | 0.110 |
| Five floors, five five-meters bays, and structural system (a) | 1.040 | 0.095 |
| Ten floors, five five-meters bays, and structural system (a) | 0.999 | 0.100 |
| Fifteen floors, five five-meters bays, and structural system (a) | 2.580 | 0.132 |
| Five floors, five five-meters bays, and structural system (b) | 0.320 | 0.176 |
| Ten floors, five five-meters bays, and structural system (b) | 0.170 | 0.107 |
| Fifteen floors, five five-meters bays, and structural system (b) | 0.736 | 0.127 |
| Five floors, five five-meters bays, and structural system (c) | 0.322 | 0.193 |
| Ten floors, five five-meters bays, and structural system (c) | 0.192 | 0.119 |
| Fifteen floors, five five-meters bays, and structural system (c) | 0.760 | 0.123 |
| Twenty floors, five five-meters bays, and structural system (c) | 0.900 | 0.110 |
| Five floors, six six-meters bays, and structural system (a) | 0.991 | 0.081 |
| Ten floors, six six-meters bays, and structural system (a) | 0.949 | 0.085 |
| Fifteen floors, six six-meters bays, and structural system (a) | 2.470 | 0.139 |
| Five floors, six six-meters bays, and structural system (b) | 0.324 | 0.186 |
| Ten floors, six six-meters bays, and structural system (b) | 0.171 | 0.092 |
| Fifteen floors, six six-meters bays, and structural system (b) | 0.564 | 0.107 |
| Five floors, six six-meters bays, and structural system (c) | 0.330 | 0.197 |
| Ten floors, six six-meters bays, and structural system (c) | 0.152 | 0.098 |
| Fifteen floors, six six-meters bays, and structural system (c) | 0.379 | 0.100 |
| Twenty floors, six six-meters bays, and structural system (c) | 0.900 | 0.110 |

Table 6: Deviation from the conventionally computed top base shears in terms of the $\mathbf{L}_\infty$ norm (%), when the excitation is as noted in Figure 2(b).


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