Influence of the soil flexibility on seismic damage level of r/c buildings subjected to multicomponent earthquake excitation with different orientation schemes

Konstantinos Morfidis1, Konstantinos Kostinakis2, Thomas Salonikios1
1Earthquake Planning and Protection Organization (EPPO-ITSAK), 55535 Pylea, Thessaloniki, Greece
2Department of Civil Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

email: kmorfidis@itsak.gr, kkostina@civil.auth.gr, salonikios@itsak.gr

ABSTRACT: The present study investigates the level of the expected seismic damage of r/c buildings of previous decades that were designed by means of a series of simplifying assumptions which have been removed by modern codes. In particular, these assumptions are the analysis using 2D models without considering the foundation and the soil flexibility, as well as the consideration of seismic loads as horizontal static forces exclusively along the direction of the structural axes. In the present paper, the expected seismic damage in two symmetric in plan r/c buildings (one low- and one high-rise) designed on the basis of the aforementioned assumptions is determined. This calculation is made by ignoring the specific assumptions, with the aid of nonlinear time response analysis for 72 different angles of seismic excitation and by employing the Park & Ang damage index as well as the maximum interstorey drift ratio. The results of the analyses showed that the consideration of the soil flexibility affects the expected structural damage depending on the damage measure adopted. More specifically, when the Park & Ang damage index is used the soil deformability reduces the damage level, whereas in case of utilizing the maximum interstorey drift ratio the opposite conclusion applies. Moreover, the soil flexibility reduces the impact of the incident angle on the seismic damage.

KEY WORDS: R/C BUILDINGS; SOIL FLEXIBILITY; DAMAGE INDICES; SEISMIC EXCITATION ANGLE; SEISMIC DAMAGE

1 INTRODUCTION

The methodology of designing r/c buildings during the previous decades included a series of simplifying assumptions. These assumptions were necessary due to the level of the available scientific knowledge and the limited power of computer systems. Three of the most important design assumptions were the following:

(a) Modeling of buildings using models without considering the foundation or the influence of soil flexibility (i.e. considering that the vertical elements are fully fixed to the ground). For the foundation, a separate model, in which the loads of the superstructure are applied, was considered.
(b) Modeling of buildings with two separate 2D frames along the direction of their structural axes, which were defined during the process of forming the structural system.
(c) Modeling of seismic loads using horizontal static forces along the direction of the structural axes and combination of internal forces derived from the seismic action along these axes by means of simplifying methods (e.g. the 30% directional combination rule [1]).

The inadequacy of assumption (a) has been acknowledged and proved during the last decades, especially in the case of buildings founded on soft soil. Therefore, the modern codes (e.g. [2, 3]) demand the formation of a unified model that includes the superstructure, the foundation and the flexibility of the soil.

The assumption (b) is no longer the main option of the modern codes, due to the fact that, as it has been demonstrated, the influence of torsional effects caused by the eccentricities of seismic forces is considerable. It has been also shown that 2D models are incapable of approximating the torsional effects in a reliable way. In consequence, the modern codes necessitate the use of spatial models. However, they do not propose a methodology of defining the critical angle of the seismic excitation, i.e. the angle that yields the maximum values of the design internal forces. Nevertheless, it is important to notice that the response of the structural systems depends on the orientation of the seismic input with regard to structural axes. Rotating the axes along which the horizontal accelerograms are applied leads to different structural response. As it has been shown by many researchers, even for quite simple buildings, the angle of incidence can radically alter the analysis results in terms of the elastic response and design of structures (e.g. [4-7]), as well as of the inelastic response and damage level (e.g. [8-11]).

Finally, assumption (c) has been almost abandoned, since the modern codes (e.g. [2, 3]) introduce the modal response spectrum method as the main analysis method and allow for the use of static seismic forces only under very specific conditions (e.g. symmetric in plan buildings).

Yet, in spite of the fact that the assumptions mentioned above are not taken into account in recent years, there still exist a large number of r/c buildings that were designed on the basis of these assumptions during the previous decades. Therefore, it is more than essential to investigate the level of the expected seismic damage in these buildings by analyzing them without utilizing the three aforementioned assumptions by means of nonlinear time response method, taking into consideration several excitation angles. This investigation constitutes the objective of the present paper. For this purpose, two r/c buildings (one low- and one high-rise) were designed, bearing in mind the three assumptions described above. These buildings are double-symmetric and consist of r/c frames in two orthogonal directions. In one direction the frames include r/c walls, whereas they do not do so in the other, so that the horizontal stiffnesses of the buildings along these directions
are considerably different. The foundation of these buildings consists of footings connected by foundation beams.

Then, the buildings were analyzed by means of the nonlinear time response analysis without taking into consideration the aforementioned assumptions (additionally, for comparison reasons, the analyses were conducted adopting only the first assumption, i.e. for the fully fixed to the ground models). Thus, a unified model that includes the superstructure, the foundation and the flexibility of the soil was formed for each of the two buildings. The soil was considered as one of high flexibility and was modeled utilizing the Winkler model [12]. In addition, the seismic excitation was introduced in the form of accelerograms from 63 earthquakes (classified as near-fault and far-fault excitations) in 72 different incident angles (with a step of 5°). On the basis of the analyses results the expected damage indices after Park and Ang [13] were calculated. Moreover, the expected damages were calculated using the maximum interstorey drifts, which have been also extensively used as damage indicators in the international literature [14-16].

The analyses results revealed that the consideration of the soil flexibility can radically alter the assessment of the expected damage of the buildings, depending on the distance of the record to the fault rupture, the damage measure adopted to quantify the structural damage state and the special characteristics of the structure. Moreover, it was shown that the orientation of ground motion strongly affects the seismic performance and the damage level of the buildings, even if their plan-view is double-symmetric and quite simple. In general, the soil flexibility reduces the impact of the incident angle on the seismic damage.

2 DESCRIPTION OF THE ANALYSIS PROCEDURE

The procedure followed in order to achieve the goals of the present investigation consists of the following steps:

- Selection of the examined r/c buildings,
- Modeling of the elastic behavior of the structural members,
- Analysis and design of the selected buildings on the basis of the assumptions made in previous codes (i.e. without considering the foundation structure and the soil flexibility in a unified model with the superstructure and by modeling the seismic excitation using horizontal static forces along the structural axes),
- Introduction into the superstructure model of the foundation as well as of the soil flexibility based on the Winkler theory,
- Selection of the seismic excitations used for the nonlinear analyses,
- Modeling of the nonlinear behavior of the structural members,
- Analysis of the buildings using the method of nonlinear time response analysis for various angles of the seismic excitation,
- Calculation of damage indices for the structural elements, as well as for each building as a whole, with two different definitions (Overall Structural Damage Index according to Park and Ang and Maximum Interstorey Drift Ratio i.e. MIDR).

In what follows, the details of the aforementioned steps will be described in brief.
2.1 Description of the selected r/c buildings and assumptions of their elastic modeling

For the purposes of the investigation, two double-symmetric r/c buildings, with design parameters as shown in Figure 1, were chosen. The buildings have a structural system that consists of r/c frames in two orthogonal directions (axes X and Y). Along X-axis there are two r/c walls that receive approximately 65% of the base shear. Therefore, their horizontal stiffness along the Y-axis is significantly smaller than the one along the X axis. The foundation structure of the buildings consists of footings connected by foundation beams (Figure 1). The soil type was taken to be medium-dense sand.

For the modelling of the buildings, the following assumptions were taken into account: (a) the slabs behaved as diaphragms, (b) the zones in the joint regions of beams/columns and beams/walls were considered as fully rigid, (c) the introduced values of flexural stiffness corresponded to cracked r/c elements.

The soil flexibility was not taken into consideration in the design of the buildings. Thus, the buildings were considered to be fully fixed to the ground. However, according to the methodology described above, during the stage of the nonlinear analyses, both the foundation structure and the soil flexibility were modelled using the Winkler model [12]. The modulus of subgrade reaction $K_s$ was calculated utilizing the method that was introduced by Terzaghi [17]. The foundation structure was modelled assuming that the footings behaved as rigid bodies. The foundation beams were modelled using the classic finite beam elements. The soil flexibility was modelled using the Winkler model, as mentioned above. Therefore, single vertical and rotational elastic springs were placed at the geometric centre of the contact surface of the footings and the ground. Also, the foundation beams were not considered to be resting on the ground.

2.2 Analysis and design of the buildings

The buildings were analyzed and designed by employing the provisions of the old Greek codes (r/c code and seismic code). As a result, for instance, horizontal static forces along the structural axes X and Y (Figure 1) were taken into account for the seismic excitation. In addition, the seismic base shear was considered as equal to 8% of the total weight of the buildings.

It should be noted that the choice of the dimensions of the structural element cross-sections as well as that of their reinforcement was made while bearing in mind the optimum exploitation of the structural materials (steel and concrete). Therefore, the capacity ratios (CRs) of all critical cross-sections due to bending are close to 1.0 (the mean value of CRs ranges between 0.92-0.96). The professional program for r/c cross-sections analysis and design DIASK [18] was employed in the design of the sections of structural members.

2.3 Seismic records for the nonlinear time response analyses

A suite of 63 pairs of horizontal bi-directional earthquake ground motions (34 far-fault and 29 near-fault records) obtained from the PEER [19] and the European strong motion database [20] was used as input ground motion for the analyses of the buildings investigated. In order to define whether an area is in the near- or far-field the commonly used distance to the fault was adopted.

### Table 1. Far-fault records.

<table>
<thead>
<tr>
<th>No</th>
<th>Earthquake name</th>
<th>Station number</th>
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<th>Station number</th>
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<tr>
<td>1</td>
<td>Imperial Valley</td>
<td>5061</td>
<td>18</td>
<td>Coalinga</td>
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<td>21</td>
<td>Campano Lucano (Italy)</td>
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</tr>
<tr>
<td>5</td>
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<td>Preveza, Greece</td>
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</tr>
<tr>
<td>6</td>
<td>Landers</td>
<td>12331</td>
<td>23</td>
<td>Kefallinia island (Greece)</td>
<td>126</td>
</tr>
<tr>
<td>7</td>
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<td>12026</td>
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<td>Kefallinia island (Greece)</td>
<td>126</td>
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<tr>
<td>8</td>
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<td>57066</td>
<td>25</td>
<td>Spitak</td>
<td>173</td>
</tr>
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<td>9</td>
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<td>Montenegro</td>
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<tr>
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<td>11</td>
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<tr>
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<td>Strofades, Greece</td>
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<tr>
<td>17</td>
<td>Coalinga</td>
<td>36227</td>
<td>34</td>
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<td>214</td>
</tr>
</tbody>
</table>

### Table 2. Near-fault records.

<table>
<thead>
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<th>No</th>
<th>Earthquake name</th>
<th>Station number</th>
<th>No</th>
<th>Earthquake name</th>
<th>Station number</th>
</tr>
</thead>
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<td>Northridge</td>
<td>0637</td>
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<td>24514</td>
<td>17</td>
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<td>90055</td>
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<tr>
<td>3</td>
<td>Northridge</td>
<td>90006</td>
<td>18</td>
<td>Whittier Narrows</td>
<td>90025</td>
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<tr>
<td>4</td>
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<td>90094</td>
<td>19</td>
<td>Whittier Narrows</td>
<td>90034</td>
</tr>
<tr>
<td>5</td>
<td>Whittier Narrows</td>
<td>90066</td>
<td>20</td>
<td>Friuli, Italy</td>
<td>33</td>
</tr>
<tr>
<td>6</td>
<td>Imperial Valley</td>
<td>117</td>
<td>21</td>
<td>Friuli, Italy</td>
<td>33</td>
</tr>
<tr>
<td>7</td>
<td>Cape Mendocino</td>
<td>89156</td>
<td>22</td>
<td>Friuli, Italy</td>
<td>33</td>
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<tr>
<td>8</td>
<td>Chi-Chi, Taiwan</td>
<td>101</td>
<td>23</td>
<td>Volvi, Greece</td>
<td>50</td>
</tr>
<tr>
<td>9</td>
<td>Chi-Chi, Taiwan</td>
<td>028</td>
<td>24</td>
<td>Volvi, Greece</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>Chi-Chi, Taiwan</td>
<td>049</td>
<td>25</td>
<td>Aktion, Greece</td>
<td>121</td>
</tr>
<tr>
<td>11</td>
<td>Erzincan, Turkey</td>
<td>95</td>
<td>26</td>
<td>Spatik</td>
<td>173</td>
</tr>
<tr>
<td>12</td>
<td>Loma Prieta</td>
<td>47380</td>
<td>27</td>
<td>Umbria Marche (Italy)</td>
<td>221</td>
</tr>
<tr>
<td>13</td>
<td>Loma Prieta</td>
<td>47381</td>
<td>28</td>
<td>Duzce, Turkey</td>
<td>553</td>
</tr>
<tr>
<td>14</td>
<td>Loma Prieta</td>
<td>47125</td>
<td>29</td>
<td>Duzce, Turkey</td>
<td>3139</td>
</tr>
</tbody>
</table>
More specifically, far-fault ground motions were considered the records at more than 15km from the fault trace, as the Uniform Building Code [3] suggests. Similarly, the near-fault motions were recorded at less than 15km from the fault trace. The seismic excitations, which have been chosen from worldwide well known sites with strong seismic activity, were recorded on soil type C, which corresponds to medium-dense sand according to EN1998-1 [2] and have magnitudes (Mₚ) between 5.5 and 7.8. The ground motion set employed was intended to cover a variety of conditions regarding tectonic environment, modified Mercalli intensity and distance to fault rupture, thus representing a wide range of intensities and frequency content. Another important aspect considering the selection of the seismic excitations is that they provide a wide spectrum of structural damage to the buildings analyzed in the present study. The characteristics of the input ground motions are shown in Tables 1 and 2.

It should be noted that, as ASCE 41-06 proposes [21], the uncorrelated horizontal components of ground motions have been used as seismic input in the present study. The accelerograms were scaled to Peak Ground Acceleration PGA = aₖS=0.24g; 1.15=0.276g, where aₖ and S are the design ground acceleration (for the seismic zone II of the Greek territory) and the soil factor (for soil type C) respectively, which are suggested by EN1998-1 [2] and EN1998-3 [22].

2.4 Modeling of the nonlinear behavior and analyses of the buildings

Plastic hinges, which are located at the column and beam ends as well as at the base of the walls, were used to model the material inelasticity of the members by means of the Modified Takeda hysteresis model [23] (Figure 2(a)). It is important to notice that the effects of axial load-biaxial bending moments (P-M-M) interaction at column and wall hinges were taken into consideration by means of the P-M-M interaction diagram shown in Figure 2(b), which is implemented in the software used to conduct the analyses [24]. The plastic moments as well as the parameters needed to determine the P-M-M interaction diagram of the vertical elements' cross sections were calculated using appropriate software [25].

Figure 2. Moment (M) - Rotation (θ) relationship [23] (a) and P-M-M interaction diagram [24] (b).

The buildings were analyzed by Nonlinear Time Response Analysis (NTRA) for each one of the 63 earthquake ground motions. The analyses were performed with the aid of the computer program Ruaumoko [24]. Furthermore, as the seismic incident angle with regard to structural axes is unknown, the two horizontal accelerograms of each ground motion were applied along horizontal orthogonal axes forming with the structural axes an angle θ=0°, 5°, 10°, …, 355°. Thus for each building and each pair of accelerograms 72 orientations were considered. As a consequence a total of 9,072 NTRA (2 buildings x 63 earthquake records x 72 incident angles) were conducted in the present study.

For each ground motion and incident angle, the damage state of the two buildings was determined. The seismic performance is expressed in the form of the following parameters: i) the Maximum Intersorey Drift Ratio (MIDR) and ii) the Overall Structural Damage Index (OSDI). The aforementioned structural response parameters, which have been used by many researchers for the inelastic assessment of structures, lump the existing damage in all the cross-sections in a single value.

The MIDR, which is generally considered an effective indicator of global structural and nonstructural damage of r/c buildings [14-16] corresponds to the maximum drift among the four perimetric frames of the buildings investigated. The values of this damage indicator have been classified according to the European Macroseismic Scale of 1998 [26], by considering the damage levels shown in Table 3.

Table 3. Relation between MIDR and damage state.

<table>
<thead>
<tr>
<th>Degree of damage</th>
<th>MIDR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>Slight</td>
<td>0.25-0.5</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>Heavy</td>
<td>1.0-1.5</td>
</tr>
<tr>
<td>Destruction</td>
<td>&gt;1.5</td>
</tr>
</tbody>
</table>

Moreover, the overall structural damage index (OSDI) of the buildings was determined. Note that, in general, damage indices estimate quantitatively the degree of seismic damage that a cross-section as well as a whole structure has suffered. A damage index is a quantity with zero value when no damage occurs and a value of 1 when failure or collapse occurs. In the present study, the OSDI was computed as a weighted average of the local damage indices at the ends of each structural element. The dissipated energy was used as a weight factor (Eq. 1) [27-30]:

\[
\text{OSDI} = \sum_{i=1}^{n} \left( \frac{E_{T_i}}{E_{T_i}} \sum_{i=1}^{n} E_{T_i} \right)
\]

where LDIᵢ is the local damage index at cross section i, Eₜᵢ is the energy dissipated at the cross section i and n is the number of cross sections at which the local damage is computed. For the LDI, the widely used Park and Ang damage index [13] modified by Kunnath et al. [31] has been used. The advantages of this damage index are its simplicity and the fact that it has been calibrated against a significant amount of observed seismic damage. Park et al. [30] suggested the detailed classification presented in Table 4 concerning the values of damage index and the damage state of the structure. It is also important to mention that the Park and Ang damage index was tested experimentally.

<table>
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<tr>
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</tr>
<tr>
<td>Destruction</td>
<td>&gt;1.5</td>
</tr>
</tbody>
</table>
The graphs, which concern the two buildings considered in the present study, are plotted separately for the far-fault and the near-fault earthquake records.

From the above figure it is obvious that the consideration of soil flexibility led to less severe structural damages of the buildings (smaller values of average OSDI). The above conclusion is valid for all the orientations of seismic records investigated regardless of whether they were recorded in near-or far-field area. The only exception is the average OSDI for incident angle 115° of the building 8SF under near-fault ground motions (Figure 3(b)). The reduction of the damage severeness due to the soil flexibility can be significant, for example note that the degree of damage of the building 3SF-FF under far-fault seismic records was severe according to the classification of Table 4 (OSDI > 0.4), whereas when the flexibility of the soil was taken into account (building 3SF-EF) the average OSDI did not exceed the value of 0.4 (moderate damage) for any incident angle (Figure 3(a)). Similarly, when the building 3SF was subjected to near-fault ground motions the structural damage was severe for a large number of incident angles, in contrary to the case of considering the soil flexibility, where the structure did not suffer severe damage at any orientation of the earthquake strong motions. Similar results can be seen in the case of the building 8SF. In particular, the values of OSDI for the building 8SF under far-fault records range between 0.28 and 0.35 when it was considered to be fully fixed to the ground and between 0.22 and 0.26 when the soil flexibility was taken into account. Similarly, the values of OSDI for the same building under near-fault records range between 0.29 and 0.38 when the building is considered as fully fixed to the ground and between 0.25 and 0.35 when the flexibility of soil was considered. Of great importance is also the fact that the difference between the values of OSDI calculated with or without the consideration of soil flexibility is slightly larger in case of the low-rise building 3SF.

Another significant observation made from Figure 3a (far-fault records) is that the bandwidth of the interval where the values of OSDI for each building fluctuate is larger for the buildings which are fully fixed to the ground, which means that the impact of the incident angle on the structural damage (value of OSDI) is more significant when the soil flexibility is ignored.

As far as the distance between the record and the fault is concerned we can see that near-fault ground motions led for the majority of the incident angles to slightly larger OSDI of the building 8SF than the one produced when the far-fault records are used as seismic input. This observation is valid irrespective of whether the soil deformability is taken into account or not. However, in the case of the building 3SF-FF the opposite conclusion applies, whereas when the soil flexibility is considered (building 3SF-ES) no general trend is observed.

In Figure 4 the variation of average values of MIDR over all earthquake records with the incident angle.
the soil flexibility resulted in more significant damage than
the one produced when the building is considered as fully
fixed to the ground. More specifically, note that the values of
average MIDR when the far-fault records are used range
between 0.96% and 1.10% for the building 3SF-FF (fully
fixed to the ground) and between 1.10% and 1.21% when the
soil flexibility is taken into account (building 3SF-ES). The
respective values in case of the near-fault ground motions
range between 0.94% and 1.23% for the building 3SF-FF and
between 1.17% and 1.41% for the building 3SF-ES.

Regarding the high-rise building 8SF, from the Figure 4 it is
obvious that the consideration of the soil flexibility does not
lead to significant change in the seismic damage level. Notice
that the impact of the soil deformability on the values of
average MIDR is negligible in the case of the far-fault
records, whereas it depends on the incident angle when the
near-fault ground motions are used, since there are
orientations that lead to larger values of MIDR when the
flexibility of the soil is considered as well as orientations for
which the opposite conclusion applies.

From the above, it is evident that the results of the damage
assessment depend on the parameter of inelastic response
adopted. So, the choice of the appropriate parameter that will
be used as an indicator of seismic damage is of particular
importance. This disagreement between the results derived
using OSDI or MIDR is due to the fact that these damage
measures attempt to quantify a complicated natural
phenomenon in a different way: the computation of OSDI is
based on the degree of local seismic damages at the cross-
sections of the building, whereas the MIDR is based on
deformation and displacement demands of one or more
storeys.

Moreover, Figure 4 clearly shows that, there are cases
where the bandwidth of the interval where the values of
average MIDR for each building fluctuate is larger when the
soil flexibility is ignored. The impact of the soil flexibility is
particularly obvious in the case of the building 8SF subjected
to near-fault ground motions (Figure 4(b)), where we can
notice that the interval where the values of MIDR fluctuate is
0.75%-0.96% for the building 8SF-FF (fully fixed to the
ground), whereas it is reduced to 0.85%-0.95% for the
building 8SF-ES. Another significant observation made from
Figure 4 is that near-fault ground motions led to worse
damage state of the structures for the vast majority of the
incident angles than the one produced when the far-fault
records are used as seismic input irrespective of whether the
soil deformability is taken into account or not.

Concerning the influence of the orientation of strong
motions on the damage response, as a general observation
from Figures 3 and 4, it is deduced that, with the exception of
MIDR of the building 3SF under near-fault seismic records
(Figure 4(b)), the graphs don’t reveal any strong impact. This
observation can be attributed to the fact that taking the
average values of the examined response parameters over all
the seismic motions normalizes the peaks of individual
records and so fails to reach reliable conclusions. In order to
better quantify the influence of the incident angle on the
structural response of the buildings investigated the Maximum
Relative Variation MRV for every earthquake record is
defined as:

\[
\text{MRV}_{\text{DRP}} = \frac{\text{max DRP} - \text{min DRP}}{\text{min DRP}} \times 100\% 
\]

where maxDRP and minDRP: the maximum and the
minimum Damage Response Parameter (DPR) OSDI or
MIDR over all the orientations of the ground motion.

Figures 5 and 6 depict the average values of MRV(%) over
all seismic records for the two buildings investigated. The
results are presented separately for near- and far-fault ground
motions, for the case of considering or not the soil
deformability as well as for the two different damage
indicators considered.
Observing the above figures, it is very important to notice that the average values of the MRV$_{OSDI}$ range between 128% and 191% for the building 3SF and between 97% and 171% for the building 8SF. Similarly, the values of MRV$_{MIDR}$ range between 63% and 120% for the building 3SF and between 38% and 78% for the building 8SF. These values of MRV clearly indicate that the incident angle of the excitation strongly affects the seismic performance and the damage level of the buildings, even if their plan-view is double-symmetric and quite simple.

The extent at which the orientation of the seismic records influences the damage response depends on the consideration or not of soil flexibility, the distance of the record to the fault rupture and the damage measure adopted to quantify the structural damage state. More specifically, from Figures 5 and 6, it is shown that when the soil flexibility is taken into account the values of MRV are smaller for both OSDI and MIDR, thus indicating that the soil deformability reduces the impact of the incident angle on the seismic damage, something that is in agreement with the observations made for Figures 3 and 4, as mentioned above. This reduction, which seems to be larger when the MIDR is adopted, can be very significant depending on the distance between the record and the fault and the special characteristics of the structural system. Note for example that the average value of MRV$_{MIDR}$ is 120% for the building 3SF-FF under far-fault records, whereas the respective value in the case of accounting for the soil flexibility is 70% (Figure 6).

Another conclusion derived from Figures 5 and 6 is that the impact of the seismic orientation on the structural damage is stronger for the low-rise building 3SF. Furthermore, regarding the distance between the record and the fault, no certain trend was revealed, since it depends on the building, the consideration or not of the soil flexibility and the damage response parameter adopted. For example, note that, when the OSDI is used as damage measure the MRV attains larger values for the far-fault records in case of the building 8SF-FF (fully fixed to the ground) and the building 3SF-ES (resting on flexible soil). The opposite applies for the building 8SF-ES and the building 3SF-FF (Figure 5). Similarly, when the MIDR is used as damage measure, it attains larger values for the far-fault records in case of the building 3SF, whereas the opposite applies for the building 8SF (Figure 6).

4 CONCLUSIONS

The influence of the soil flexibility on the nonlinear seismic response of r/c buildings was investigated. More specifically, the investigation focuses on the level of expected structural damage of existing buildings designed according to old seismic codes. To accomplish this purpose, two r/c buildings, one low-rise and one high-rise are investigated. The buildings have been designed using the assumption that they are fully fixed to the ground. Nonlinear time response analyses under 63 bidirectional ground motions were performed, taking into consideration the orientation of seismic components with regard to the structural axes. In order to account for the influence of the soil flexibility, each one of the buildings is modeled considering i) fully fixed vertical elements to the ground and ii) foundation resting on soil with high flexibility. The structural damage of the buildings was expressed in terms of the overall structural damage index (OSDI) according to Park and Ang, as well as the maximum interstorey drift ratio (MIDR). The following conclusions were derived from the comparative assessment of the results:

- The assessment of seismic damage can lead to different results depending on the parameter used to describe and quantify the damage state of the structure. So, the choice of the appropriate damage measure is of great significance. The aforementioned disagreement is attributed to the fact that these damage measures attempt to quantify a complicated natural phenomenon in a different way.

- The consideration of the soil deformability led to smaller values of average OSDI than the values produced when the buildings are modeled as fully fixed to the ground. The above conclusion is valid for all the orientations of seismic records investigated regardless of whether they were recorded in near- or far-field area. The difference between the values of OSDI calculated for the buildings fully fixed to the ground and for the buildings resting on flexible soil is slightly larger in case of the 3-storey building 3SF.

- When the MIDR is adopted as a descriptor of the building’s damage state, concerning the 3-storey building 3SF, the consideration of the soil flexibility resulted in more significant damage than the one produced when the soil flexibility is ignored. As far as the high-rise structure regards, the existence of the elastic foundation does not lead to significant change in the seismic damage level.

- The incident angle of the excitation strongly affects the seismic performance and the damage level of the buildings, even if their plan-view is double-symmetric and quite simple. The extent at which the orientation of the seismic records influences the damage response depends on the consideration or not of the soil flexibility, the distance of the record to the fault rupture and the damage measure adopted to quantify the structural damage state. The soil flexibility reduces the impact of the incident angle on the seismic damage. This impact is stronger for the low-rise building 3SF. Furthermore, regarding the distance between the record and the fault, no certain trend was revealed. It must be noted that the aforementioned conclusions are valid for the buildings, the level of soil flexibility and the ground motions used in the present study.
REFERENCES


