EFFECTS OF GROUND MOTION EVENT-TYPE ON STRUCTURAL RESPONSE DUE TO THE INFLUENCE OF HIGHER MODES

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Abstract

Seismically active regions, such as Japan or British Columbia in Canada, are exposed to more than one type of earthquake event, including shallow crustal as well as deep in-slab and interface subduction earthquakes. Ground motions from each one of the three earthquake types have unique properties such as intensity, frequency content and duration. If the same structure is subjected to each of these types of earthquakes, the differences in ground motion properties may result in different structural responses, particularly in terms of the induced forces and displacements. To perform transient seismic response-history analyses of structures located in south-western British Columbia, the 2015 edition of the National Building Code of Canada requires the selection and scaling of three suites of ground motion records, one for each of the three sources of earthquakes contributing to the regional seismic hazard. In this paper, we examine the influence of the ground motion from each earthquake type on the seismic response of medium- and high-rise buildings with a focus on the base shear amplification caused by higher mode effects. For this purpose, a data set of selected historical ground motion records representing the three earthquake types is first compiled. When necessary, the records underwent one or more correction process(es) to be suitable for response-history analysis of structures in south-western British Columbia. The responses obtained from single- and multi-degree of freedom linear elastic models of a 9-storey building with steel braced frames are examined in the article and the results reveal how the mean period, or the frequency content, of the records of each suite affects the peak base shear demand as well as the peak roof horizontal displacements. The example studied clearly shows the importance of considering ground motion records from all contributing sources of earthquakes in the response-history seismic analysis of structures in regions exposed to different types of earthquake events.

Keywords: Ground Motions; Higher Mode Effects; Frequency Content; Subduction Zone; Response-History

1. Introduction

The increasing popularity of performance-based seismic design and analysis approaches [1-5], has resulted in the emergence of dynamic response-history analysis as a prominent method to determine structural response to seismic ground shaking. Ground motion records are key elements in dynamic response-history analysis procedures. Accordingly, besides the accuracy of the numerical model, selection of appropriate ground motion records that represent the regional seismic hazard, plays a major role in the quality and applicability of the results obtained from such analyses. In addition to magnitude-distance scenarios and local site conditions, attention should be devoted to the earthquake types as ground motion records from different tectonic sources do not necessarily exhibit the same characteristics which, in turn, can result in different structural responses [6-8]. There are four main types of earthquakes that are of interest to the structural engineering community: (i) shallow crustal intra-plate earthquakes in regions with moderate to low seismic activity such as those affecting eastern North America or Australia for which the mechanism is not clearly defined due to the absence of distinguishable faults; (ii) shallow crustal earthquakes caused by active faults such as those occurring in western North America, Italy, Turkey, or Iran; (iii) in-slab subduction earthquakes, i.e. those occurring within the subducting plate in areas where an oceanic and a continental tectonic plate converge and the former slips under the latter, as seen along the coasts of western North America, Chile, and Japan; and (iv) interface subduction earthquakes which happen in the contact interface between the subducting oceanic and the continental plates in a subduction zone. Thus, for a response-history analysis to bear appropriate results, the ensemble of ground motion records adopted should represent all earthquake types that are expected in the specific region where the structure is located.

Shallow crustal earthquakes from active faults, in-slab subduction earthquakes, and interface subduction events are the main contributors to the seismic hazard in seismically active regions such as Japan, or British Columbia in Canada. Examples of past events affecting these regions include the 1994 Northridge shallow crustal event, the 2001 Nisqually deep in-slab subduction earthquake, and the 2011 Tohoku interface subduction event. Ground motions from each one of the three earthquake types have unique properties such as intensity, frequency content and duration. Interface subduction events generally are of large magnitude and generate long duration ground motions. For instance, the 2011 Tohoku earthquake in Japan had a magnitude $M_w = 9.1$ and ground shaking lasted for approximately six minutes. Ground motions from in-slab subduction events are, in general, characterized by very high frequencies, which could be critical for short-period structures such as dams, low-rise buildings, and small or medium span bridges. Such ground motions can also create significant higher mode effects such as large storey shear demands in tall structures. In addition, in-slab events are usually characterized by relatively deep hypocenters. The 2005 Tarapaca earthquake in Chile is an example of an in-slab event with a magnitude $M_w = 7.8$ and a depth of about 100 km. Contrary to in-slab events, motions from interface subduction events are characterized by relatively lower frequency contents which may affect structures with longer periods of vibration such as tall buildings, long and flexible bridges, e.g. suspension bridges, and isolated structures.

Considering dynamic response-history analysis of structures located in regions such as British Columbia, the 2015 edition of the National Building Code (NBC) of Canada [9] requires the selection and scaling of suites of ground motion records for each earthquake type contributing to the regional seismic hazard. Given the different characteristics of each type of ground motions, as discussed above, different responses can be expected for a given structure subjected to ground motions from the different types of earthquakes, particularly in terms of the induced forces and displacements. As higher mode effects increase storey shears induced in medium- and high-rise buildings, this article examines the influence of ground motion event-type on the seismic response of a building in terms of higher mode effects. For this purpose, a data set of selected historical ground motion records representing the three event types is first compiled. When necessary, the records underwent one or more correction process(es) to become suitable for response-history analysis of structures in south-western British Columbia. The procedure outlined in the guidelines provided in the Commentary to the 2015 NBC [10] is followed to construct the suites of records. The responses obtained from linear elastic analysis of single- and multi-degree of freedom models of a 9-storey building with steel braced frames are used to examine how the mean period, as a frequency content indicator for ground motion records, correlates with the induced base shears and peak roof horizontal displacements.

2. Building analyzed

A nine-storey braced frame office building presented in [11] was selected for this study. This is the same building considered in [12] modified by: (i) omitting the penthouse structure; (ii) replacing the perimeter moment frames acting in the east–west direction by buckling restrained braced frames (BRBF) positioned in a chevron (inverted-V) bracing configuration; and (iii) rotating the columns on the east–west perimeter walls by 90°. The modified plan is 46 m by 46 m square and the building is 41 m tall including the basement level and the relatively taller first storey which is common to office buildings. As illustrated in Fig. 1, the lateral force-resisting system of the studied building consists of braced frames on the north and south exterior faces (identical frames) of the building as well as moment resisting frames on the east and the west sides. The structure is designed in accordance with the provisions of NBC 2015 and the CSA S16-14 steel design standard [13]. The structure is located on a class C (soft rock or firm ground) site in Vancouver, British Columbia, Canada. The first four vibration periods of the structure are T_1 = 1.86 s, T_2 = 0.66, T_3 = 0.32 s, and T_4 = 0.26 s, respectively.

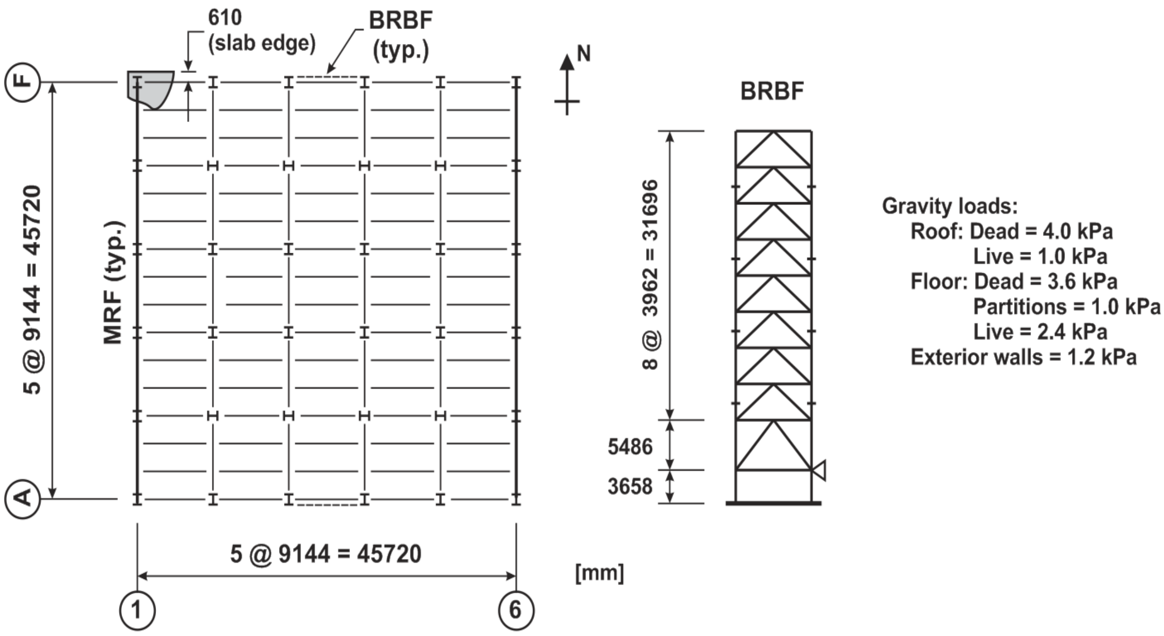

Fig. 1 – Plan and elevation views of the studied structure

3. Ground motion data

A large number of databases and strong motion observation networks were consulted to obtain ground motion recordings from in-slab and interface subduction events that have occurred at different locations around the globe. The resulting database contains approximately 9500 horizontal and vertical ground motion accelerograms from events having a magnitude range of 5.1 ≤ M_w ≤ 9.1 and a rupture distance range of 10 ≤ R_{rup} ≤ 1000 km. Fig. 2 shows the magnitude-distance distribution of these events which are mainly from the *Pacific Ring of Fire*. The majority of the accelerograms, roughly 75%, represent NEHRP (FEMA 450) [14] site classes C and D, i.e. 360 < V_{S30} < 760 m/s and 180 < V_{S30} < 360 m/s, respectively with V_{s30} being the average shear-wave velocity in the uppermost 30 m of the subsurface profile of the recording site. When necessary, the accelerograms underwent one or more correction process(es), e.g. base-line correction and high- and low-pass filters, to be suitable for response-history analysis.

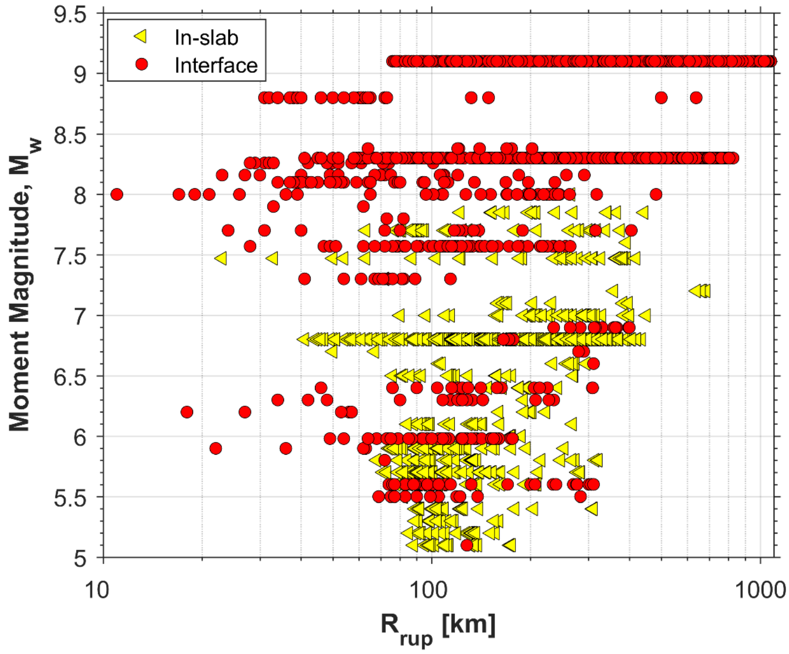

Fig. 2 – Magnitude-distance distribution of the compiled database of subduction in-slab and interface ground motion records

To perform the analysis, a subset of accelerograms from the compiled database, roughly representing the mean M_w-R_{rup} scenarios for Vancouver, British Columbia, Canada and a NEHRP site class C was first formed. The mean M_w-R_{rup} scenarios were obtained from the hazard deaggregation results based on the model developed in [15]. The reader is referred to [6] for the M_w-R_{rup} scenarios determined at different periods. The subset consists of a suite of fifty accelerograms from in-slab events having a magnitude range of $6.5 \leq M_w \leq 7.3$ covering distances of $47 \leq R_{rup} \leq 89$ km, and a suite of fifty interface accelerograms with a magnitude range of $8.3 \leq M_w \leq 9.1$ and distances of $120 \leq R_{rup} \leq 160$ km. In addition to this subset, the PEER NGA West 2 database (https://ngawest2.berkeley.edu) was used to form a third suite of fifty ground motion records from shallow crustal events. The selected crustal records had a magnitude range of $6.6 \leq M_w \leq 6.93$ and covered distances of $10 \leq R_{rup} \leq 23$ km. Fig. 3 presents the acceleration response spectra of the selected records in each suite along with their mean. Adopting such a large number of records would result in an increased reliability of the analysis outcome as the standard error of the mean of the results is inversely proportional to the square root of the number of samples. It would also give the possibility to observe a wide range of structural response.

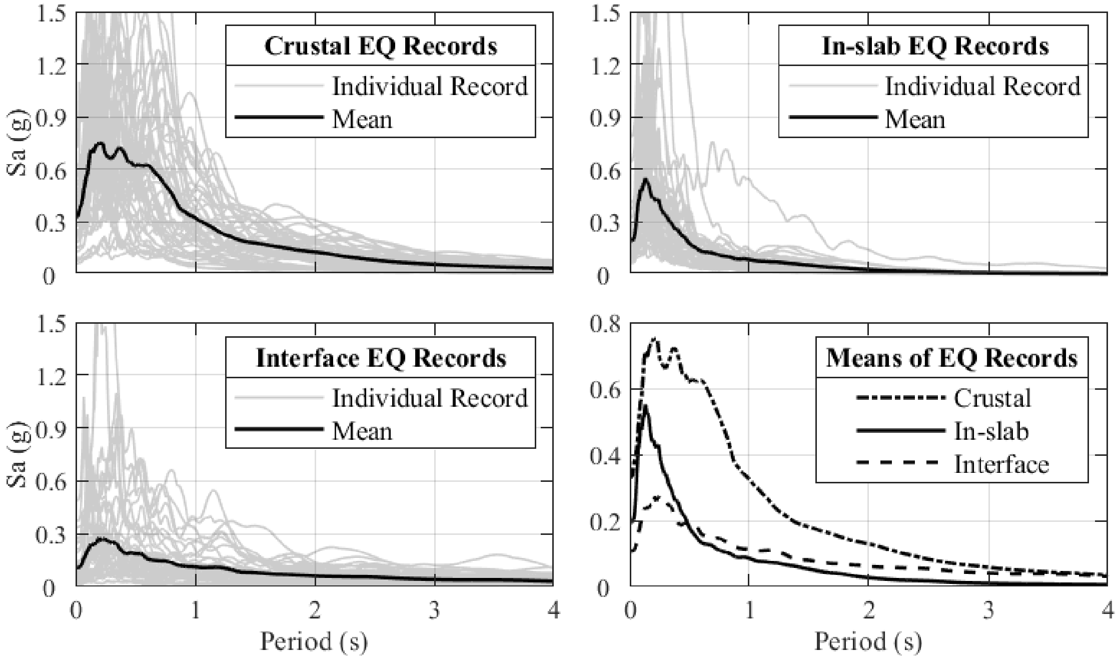

Fig. 3 – 5% damped acceleration response spectra of the 3 suites of 50 records selected for this study.

4. Analyses and results

The next step in the study of the influence of ground motion event type on structural response due to higher mode effects was the construction of the numerical model of the building. To this end, a two-dimensional planar multi-degree-of-freedom (MDOF) representation of the building structure was created in SAP2000 [16]. In this study, we focused on the response of the building to seismic excitations in the east-west direction. As a result, the main structural elements considered in the numerical model were the BRBFs acting in the east-west direction. The MDOF model of the BRBF consisted of elastic frame elements representing the steel columns and girders. The braces were modelled using linear link elements that were assigned the elastic axial stiffness of the buckling restrained bracing members.

Two sets of analyses were conducted. For the first series of analyses, the 5%-damped elastic response spectrum of each one of the records included in the subset mentioned in Section 3 was computed using an in-house MATLAB [17] code. Thus, three sets of elastic response spectra were formed, each of which representing the response of a single-degree-of-freedom (SDOF) model of the building to ground motions from one event type. In the second series of analyses, the MDOF system was subjected to the ground motion records presented in Section 3 and Fig. 3. To minimize the effects of damping on the analysis results, linear modal superposition time-history analysis was adopted, and the viscous damping value was set equal to 5% for all modes of vibration. For the MDOF numerical model, lateral loads are assumed to be divided equally between the braced frames while the in-plane torsional effects are neglected. To be able to compare the results from the elastic MDOF system with those from the elastic SDOF system, P-Delta effects were not considered in the analyses. For each ground motion record, two series of response-history analyses were conducted on the MDOF system: (i) time-history analysis considering only the fundamental mode of vibration; and (ii) modal superposition time-history analysis considering the first 9 modes of vibration. The two series of analyses would allow the study of the effects of the higher modes of vibration. As done in the first set of analyses, i.e. on the SDOF system, the analyses mentioned in (i) and (ii) above, were performed in three sets to account for the ground motion event types.

To examine the influence of the ground motion event type on structural response including higher modes effects, the first response parameter considered is the peak horizontal roof displacement. Therefore, for each record in each suite of ground motions, first the roof displacement of the MDOF system, Δ_{MDOF}, the spectral displacement of the SDOF system, S_d, and the participation factor of the first mode of vibration of the MDOF system, PF_1, were determined. Next, the ratio of Δ_{MDOF} to $\Delta_{SDOF} = S_d \times PF_1$ was computed. A ratio larger than 1.0 implies that roof displacements are increased by higher mode response.

Fig. 4 presents the ratios calculated from the analyses results for each ground motion of each type. The comparison of the mean ratios indicates that in-slab events, through invoking higher mode effects, had the largest influence on the structure roof displacements, with a 10% increase in roof displacement amplitudes. This is mainly attributed to the high frequency content of the in-slab ground motion records. Contrary to the in-slab records, the relatively low frequency nature of the interface records resulted in the lowest impact of higher modes on peak roof displacements. In general, crustal and interface records produced the highest and lowest variability, respectively, in the roof displacements. Fig. 4 also shows that, in terms of variability and dispersion of the results, two of the crustal records, produced the largest individual ratios. This observation was further investigated by determining the mean period T_m [18] for the crustal records. The results are presented in Fig. 5 and they show that the crustal records producing the largest higher mode effects on roof displacements have mean periods between the 2nd and the 3rd mode periods of the building (T_2 = 0.62 s and T_3 = 0.36 s). Hence the significant amplifications. The same exercise was done for the in-slab records and the results are also shown in Fig. 5. In this case, the largest amplitudes are associated with the records having mean periods between the 3rd and 4th mode periods of the building (T_3 = 0.36 s and T_4 = 0.26 s).

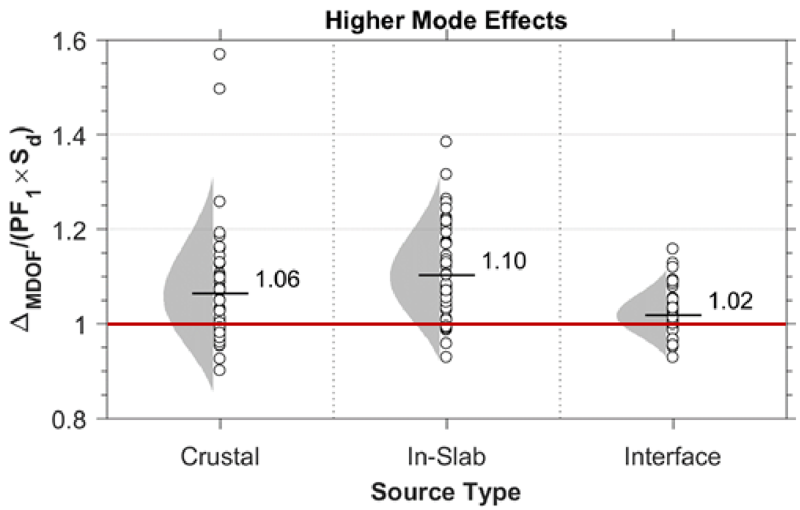

Fig. 4 - Effect of earthquake type on higher mode effects for peak roof displacement

Storey shear amplification at the structure base is the second response parameter examined to investigate the effect of the ground motion event type on structural response including the effects from higher mode response. The magnitude of base shear amplification caused by each record is determined as the ratio of the base shear induced in the linear elastic MDOF system obtained from the 9-mode analysis to that obtained from the single-mode analysis of the same system subjected to the same ground motion record. Fig. 6 illustrates the base shear amplifications obtained from the response-history analyses of the MDOF system presented as a function of ground motion event type. As was the case for roof displacements, on average, the in-slab and interface subduction records caused the highest and lowest base shear amplifications, respectively. The frequency content of the ground motions of these two event types plays a major role in the obtained responses. As shown in Fig. 6, the in-slab records created base shear amplifications as large as 4.3, while maximum amplification under the crustal earthquake reached 3.4. A comparison between Fig. 4 and Fig. 6 also shows that while the contribution of the interface subduction records to higher mode effects was of less importance for peak roof displacements (2%), base shear amplification caused by this type of event is much more pronounced (26%). In both cases, i.e. roof displacements and base shears, the mean ratios from the interface event ground motion are not as important as those from the in-slab subduction records and the shallow crustal earthquakes. To further investigate the effect of the earthquake type on base shear amplification, the correlation between the mean period of the ground motions T_m and higher mode effects on base shears is examined in Fig. 7 for the in-slab ground motion records. As shown, the highest base shear amplifications produced by in-slab ground motion records are caused by records with T_m values close to the 4th mode of vibration of the MDOF system, i.e. T_4 = 0.26 s.

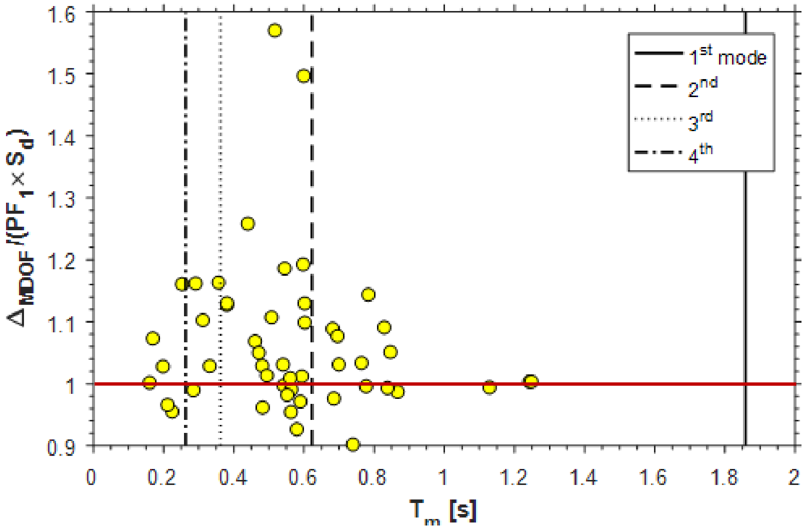

Fig. 5 – Influence of the mean period T_m of the crustal ground motion records on higher mode effects for peak roof displacements

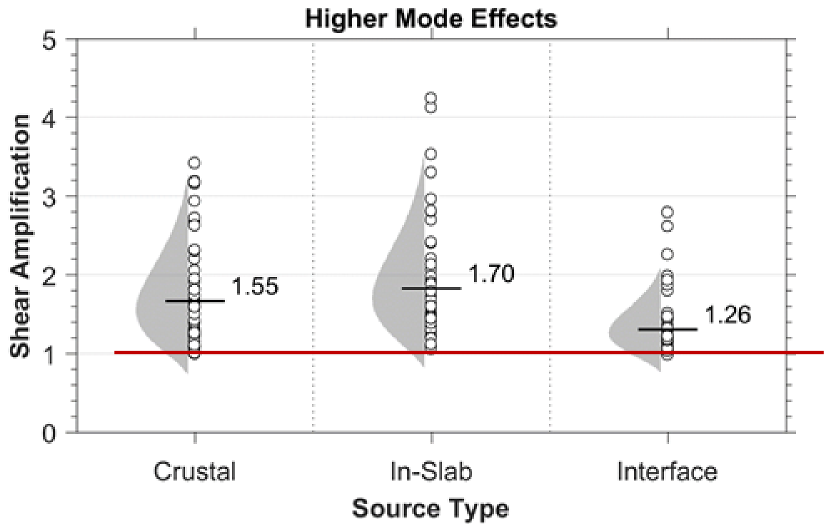

Fig. 6 – Influence of ground motion type on higher mode effects for base shears

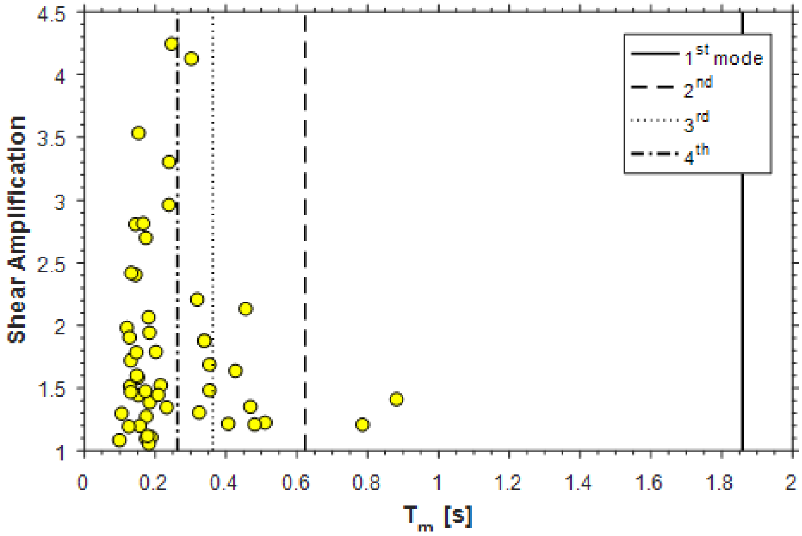

Fig. 7 – Influence of the mean period T_m of the in-slab ground motion records on higher mode effects for base shears

5. Summary and conclusions

Dynamic response-history analysis procedures have become essential for determining the structural response to earthquakes as performance-based seismic design and analysis approaches are gaining more popularity. This type of analysis requires selection and scaling of suites of ground motions that represent all earthquake types contributing to the seismic hazard for the location of interest. In regions such as British Columbia, Canada, which are affected by earthquakes occurring along the *Pacific Ring of Fire*, more than one earthquake type generally contributes to the local seismic hazard. For southwest British Columbia, shallow crustal events and Cascadia subduction ground motions must be considered, with subduction earthquakes including both deep in-slab and interface earthquakes. The most recent edition of the Canadian building code requires considering suites of ground motions representing each of the three sources of earthquake events for dynamic response analyses. Ground motions from each type of events have their specific properties, which may result in different structural responses.

In this paper, we investigated the importance of the higher mode effects on roof displacements and base shears as caused by ground motions from the three types of earthquakes. The study was performed on a 9-storey office building located in Vancouver, British Columbia with buckling restrained frames. The braced frames were represented using a single-degree of freedom (SDOF) and a multi-degree-of-freedom (MDOF) numerical models. Three suites of ground motion records each containing fifty accelerograms representing the magnitude-distance scenarios dominating the seismic hazard of the region and recorded on NEHRP site class C were compiled. The SDOF models were analyzed using the response spectrum of each selected record and the MDOF system was subjected to each one of the records through linear modal superposition response-history analysis. The results of the analyses showed that in-slab ground motion records produce the largest higher mode effects on roof displacements and base shear. This is mainly due to the high frequency content of these records that can activate the higher modes of vibration of the structure. On the contrary, interface subduction records, which generally have the lowest frequency content among the three event types, triggered the lowest higher mode contribution to the structural response. Nevertheless, it was observed that all the three types of events may lead to considerable higher mode effects on base shear, varying between 26% and 70% depending on the earthquake type. The results of this study underline the importance of the selection of suites of ground motion records representing all event types that may affect the structure location when performing dynamic response-history analysis.

6. Acknowledgements

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