VALIDATION OF VERTICAL COMPONENTS OF SCEC BBP GROUND MOTION SIMULATIONS FOR BUILDING RESPONSE ASSESSMENT

N. Gremer(1), N. Bijelić(2), C. Adam(3)

(1) *Graduate Student Researcher, Unit of Applied Mechanics, University of Innsbruck, Austria, nadia.gremer@uibk.ac.at*
(2) *Postdoctoral Scholar, Unit of Applied Mechanics, University of Innsbruck, Austria, nenad.bijelic@uibk.ac.at*
(3) *Professor, Unit of Applied Mechanics, University of Innsbruck, Austria, christoph.adam@uibk.ac.at*

Abstract

Large structural damage occurring, for instance, during the 1994 Northridge, 1995 Kobe, and 2011 Tohoku and Christchurch earthquakes has likely been exacerbated by severe vertical shaking. Yet, the characteristics of vertical ground motions and their effects on the response of buildings are not well understood and remain a contentious issue. However, there is a general consensus that such motions are definitely not beneficial and merit further study. At the same time, the lack of data that afflicts databases of recorded motions, particularly for large magnitude events and at close distances, is even more pronounced for the vertical component of ground motions than for the horizontal component. In the absence of recorded motions from past events, ground motion simulations provide a viable alternative. With the overall goal of validating and developing confidence in utilization of simulated ground motions for engineering applications, this paper examines the response of an archetype building to combined action of horizontal and vertical components of equivalent sets of simulated and recorded ground motions. The primary focus of this paper is on similar intensity measure validation of Southern California Earthquake Center (SCEC) Broadband Platform (BBP) simulations to serve as a basis for reliable building response and loss assessment studies in the future. To this end, response history analyses of an 8-story moment-resisting steel frame is performed using spectrum equivalent sets of recorded and simulated motions. Structural response parameters of interest include horizontal and vertical absolute peak floor accelerations, horizontal story drift ratios, and vertical relative peak floor displacements. The results show that simulated ground motions adequately capture the elastic displacement and acceleration demands of the investigated steel frame in horizontal as well as in vertical direction. Hypothesis testing confirmed that there are no statistically significant differences between the responses for the analyzed sets of simulated and recorded ground motions.

Keywords: numerically simulated earthquake ground motions; SCEC Broadband Platform; vertical component; seismic demand estimation

1. Introduction

Despite the fact that large structural damage during past seismic events has likely been exacerbated by severe vertical shaking exceeding the horizontal component [1-3], the majority of previous studies exclusively dealt with structural responses in the horizontal direction [4-7]. However, recent studies suggest that the vertical ground motion component can have a significant influence on structural response, especially for assessment of acceleration demands [8-11]. These studies show that the vertical modal frequencies of structures may be in tune with the high-frequency content of vertical ground motions, resulting in an amplification of the vertical accelerations along the height of the investigated structures. Thus, the vertical acceleration demands were underestimated previously, since it was assumed that the structures behave rigidly in vertical direction. Still, the characteristics of vertical ground motions and their effects on the response of buildings are not well understood and merit further study, which has hitherto also been hampered by lack of empirical data. In the absence of recorded motions from past events, numerical simulations of ground motions provide an attractive alternative.

A useful tool for utilization of numerical ground motion simulations in practical applications is the Southern California Earthquake Center (SCEC) Broadband Platform (BBP) [12]. The SCEC BBP allows the user to generate site-specific ground motions, including both the horizontal as well as vertical components, to be used for engineering analyses. Moreover, the platform has undergone extensive validation in recent years giving credence for utilization in engineering applications. For instance, study [13] focused on validation and improvements of the SCEC BBP data products for application in seismic hazard assessment. On the other hand, studies [14, 15] focused on utilization of SCEC BBP simulations in building design and risk assessments finding favorable results. For a more comprehensive overview of engineering utilizations of ground motion simulations see [16] and references therein. However, all previous validation studies only focused on the horizontal component of the ground motion and did not consider vertical responses. This paper aims to supplement the previous validation exercises by focusing on the utilization of simulated ground motions for combined action of horizontal and vertical ground motion components.

The scope of this paper is to perform similar intensity measure validation of the vertical acceleration and displacement demands by conducting response history analyses on an 8-story moment resisting steel frame with linear elastic material properties. The analyses are performed using spectrally equivalent sets of recorded and simulated ground motions. Response quantities of interest include the vertical absolute peak floor accelerations, vertical relative peak floor displacements, and horizontal drifts. Hypothesis testing is used to examine if there are statistically significant differences between responses to recorded and simulated ground motions.

2. Frame model

The analyses herein are conducted on an 8-story frame structure based on the FEMA P-695 archetype [17]. The structural properties are adopted from the steel-moment resisting frames proposed as part of NIST GCR 10-917-8 [18] and designed in accordance with [19-21]. The design of the model is based on the response spectrum analysis approach considering the maximum spectral acceleration D_{max} [18]. The structure is modelled as a 2D centerline model in *Abaqus*, where material behavior is assumed to be linearly elastic. Panel zones and reduced beam sections are not considered. The height of the first story is $h_1 = 4.57$ m, whereas all other stories have a height of $h = 3.96$ m and each bay has a width of $b = 6.10$ m. In each story of the frame the dead load is 4.31 kN/m^2, the cladding load 1.20 kN/m^2, and the floor live load is 2.40 kN/m^2, except for the roof in which the roof live load is 0.96 kN/m^2. The structural mass of the model includes 105% of the design dead loads and 25% of the live loads. The tributary area for direct load transfer to the frame structure is 28.6% of the tributary area for the total story mass (see Fig. 1 (a)). That is, 28.6% of the total story mass is distributed directly to the nodes of the frame structure in terms of lumped masses (blue area), and the remaining 71.4% of the total mass (green area) is lumped to leaning columns on both sides of the frame at a given level to achieve a symmetric frame structure. The seismic active mass is distributed along the beams and the beam-column connections, as depicted in Fig. 1 (b), since both the vertical and horizontal acceleration response of columns and beams is studied. To each node with a lumped mass the seismic active mass is assigned to two translational degrees of freedom, i.e. in the horizontal and in the vertical direction. No degree of freedom is slaved, thus, resulting in 208 degrees of freedom for the investigated frame. The lumped masses at the exterior beam-column nodes are larger than the ones at nodes along the beams given a larger corresponding tributary area. All beam nodes have the same tributary area, and thus, the corresponding lumped masses have story-wise the same value. The beam and column elements are defined as elastic Bernoulli-Euler beam elements. The cross section and the moment of inertia are taken from [18] and the Young's modulus of steel, i.e. $E = 2x10^{11}$ N/m^2 is used. This yields a fundamental horizontal period of 2.4 s and a fundamental vertical period of $T_{1v} = 0.2$ s. Further information on the structural and modal parameters of this frame model are discussed in detail in [10]. Modal damping with a constant damping ratio of 0.05 for all modes is applied.

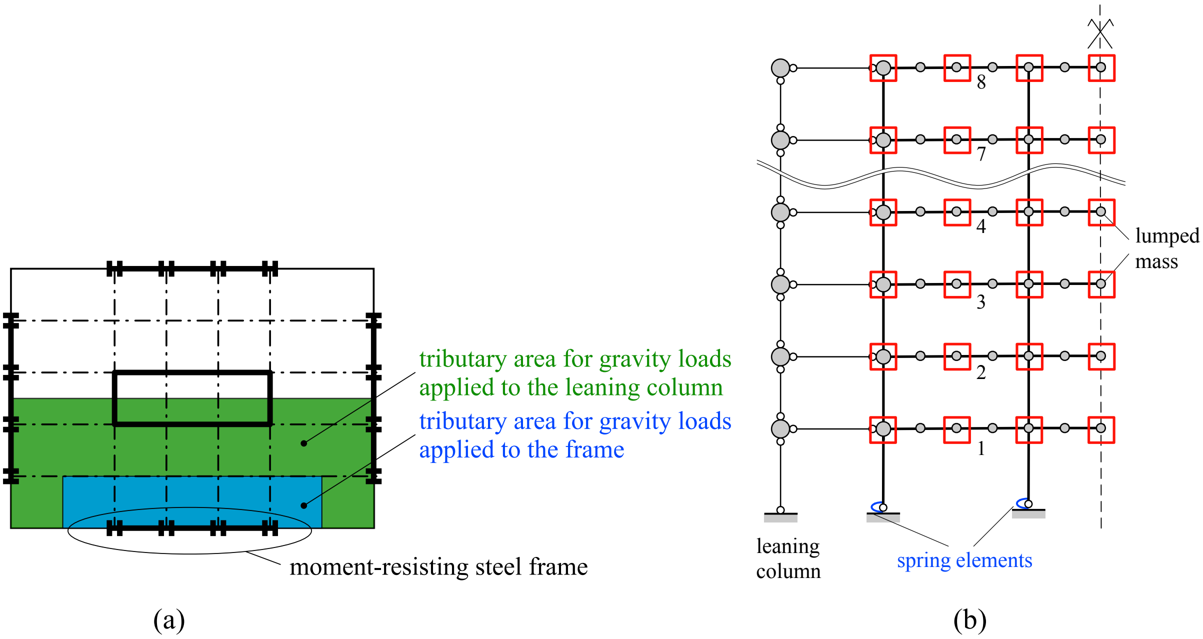

Fig. 1 - (a) Horizontal section of the underlying frame building (modified from [18]). (b) Half of the investigated 8-story 3-bay frame model with leaning columns, where the nodes considered for the response evaluation are highlighted with red squares

3. Ground motion sets

To perform similar intensity measure validation, the seismic responses are assessed using a set of recorded ground motions and a set of simulated ground motions. The two sets were developed to be equivalent in terms of elastic spectral accelerations. In other words, we explicitly control for spectral shape and intensity when selecting ground motions. Both vertical as well as horizontal component of these ground motions are used as inputs for response history analyses and both components are applied simultaneously. Simulated ground motions used in this study were obtained from a pool of simulations of past earthquake events (see Table 1) as generated using the SCEC BBP v14.3 in a larger validation study [13]. These ground motions were simulated using the GP method [22], which uses a hybrid approach to obtain broadband ground motions. Specifically, a parametrized stochastic model is used to generate the ground motion at higher frequencies ($T < 1$s) while a deterministic model (sometimes referred to as the physics-based simulation) is utilized at longer periods. The short and long frequency components are then spliced together to obtain a hybrid-broadband ground motion.

Table 1 - Sources of simulated ground motions

Source of Motions	**Scenario**	**Magnitude**	**Simulation Method**	**Number of ground motions**
SCEC BBP	Loma Prieta	6.9	GP hybrid broadband (1 Hz deterministic)	13,400
	Northridge	6.7		
	Whittier	5.9		
	North Palm Springs	6.1		
	Landers	7.3		

To develop a set of simulated ground motions, herein referred to as the BBP set (see in Fig. 2 (a) and (d)), the starting point for selection was a set of 90 recorded ground motions developed in previous studies [8,10] that focused on the assessment of the vertical acceleration response. This recorded set, referred to herein as the initial NGA set, was assembled by Moschen et al. [8] focusing on the characteristics of vertical ground motion components. Specifically, these recorded ground motions were selected with a multi-objective optimization procedure [23] that fits the median of the vertical ground motion component in the period range from 0.025 s to 0.3 s to the normalized vertical response spectrum (NEHRP-spectrum [24]) for the site of Century City, Los Angeles. Further, the dispersions were required to match a predefined target dispersion of 0.8 across this period range. The seismological characteristics on which the selection is based are listed in [8], and no constraints were imposed on the horizontal components of the ground motions during the selection. The resulting set is especially suitable for the estimation of the vertical seismic response for structures whose vertical fundamental period is in the range of the matched period range 0.025 s $\leq T_{1v} \leq$ 0.3 s. The vertical fundamental period of 0.2 s of the considered 8-story frame falls into this period range.

To develop the simulated BBP set, for each recorded ground motion from the initial NGA set a best matching simulated motion was found in terms of the horizontal and vertical spectral accelerations. That is, each ground motion was matched separately, so that the spectral values exhibit the smallest error sum of squares, with weights of 50% given to the horizontal and the vertical component, respectively, while no constraints were imposed on the scaling factors. This yields the BBP set whose horizontal component is displayed in Fig. 2 (a) and the vertical component is shown in Fig 2 (d), where thin gray lines represent the response spectrum of a single record, and bold lines refer to the statistical measures (median, 16th percentile, 84th percentile). Even though this selection approach of individually matching the ground motions aims to ensure that the two sets are in close agreement (in terms of medians and dispersions of spectral accelerations as well as inter-period correlations), discrepancies between the initial NGA set (not shown in the figures) and the selected BBP set were observed. Specifically, the medians and the 84th percentile of these two ground motion sets exhibited significant differences in the period range of 0.05s and 0.7s of the vertical response spectrum and also around the period of 0.2 s of the horizontal response spectrum.

In an effort to achieve better agreement between the simulated and recorded ground motion sets to be used in the validation exercise, the same selection procedure was repeated but this time the selected BBP set was used as a target for selection of recorded ground motions. The resulting set of recorded ground motions contains 90 records from the PEER NGA database [25] and is referred to as the NGA ground motion set, as shown in Fig. 2 (b) and (e). Comparison of statistical measures of the selected NGA and BBP sets are given in Fig. 2 (c) and (f). The horizontal as well as the vertical components show good agreement in terms of the median and the 16th percentile, while the 84th percentile shows slight differences in the period range of 0.1 to 0.7. The largest difference of the 84th percentile of the horizontal component is 19.14% at a period of 0.2 s and of the vertical component it is 23.16% at a period of 0.7. Note that the median of the vertical component of both utilized ground motion sets is close to the normalized vertical NEHRP response spectrum [24]. As such, the sets are suitable to assess the vertical seismic response of the considered frame.

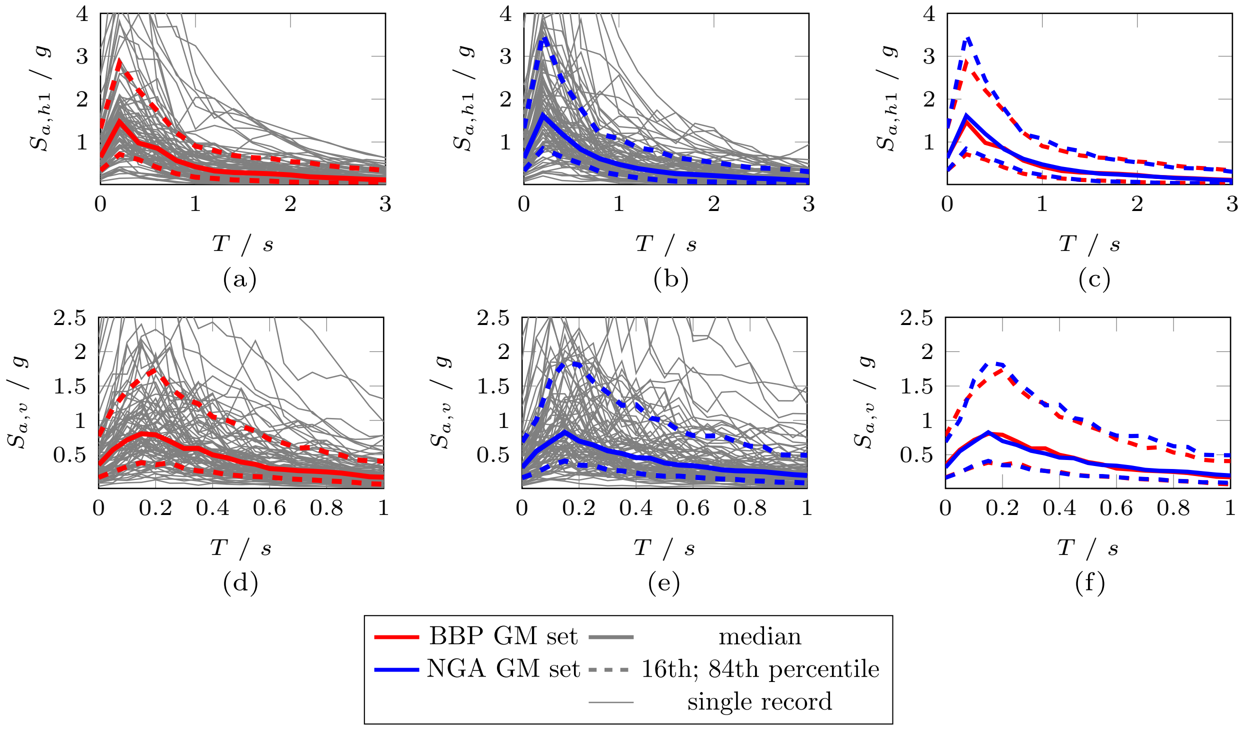

Fig. 2 - Response spectra of the simulated BBP ground motion set ((a) and (d)), the recorded NGA ground motion set ((b) and (e)) and the comparison of the two utilized response spectra ((c) and (f))

4. Results

Response history analyses are performed to estimate the absolute vertical and horizontal peak floor acceleration demands (referred to as PFA_v and PFA_h, respectively), the horizontal drifts (IDR_h), and the relative vertical peak floor displacements ($PFD_{v,rel}$) of the considered frame model. The analyses are conducted by simultaneously imposing the horizontal and vertical ground motion components of the utilized BBP and NGA ground motion sets. Similarity between the results are examined graphically while hypothesis testing is used to test whether there are statistically significant differences between responses to the recorded and simulated ground motion sets.

4.1. Acceleration response

The absolute peak floor acceleration response at the exterior column line of the 8-story frame model is shown in Fig. 3. The horizontal axis shows the absolute *PFA* in the unit of m/s^2, while the ordinate represents the height of the examined structure normalized with respect to its total height. The thin gray lines represent the absolute peak response of individual ground motions, while the bold solid lines show the median and the dashed lines the 16^{th} and 84^{th} percentile. The responses of the recorded NGA ground motion and the simulated BBP set are indicated in blue and red, respectively. In Fig. 3 (a) and Fig. 3 (b) the horizontal component of the response is shown. The median response of all stories is smaller than the peak ground acceleration, except for the top story where the acceleration demand exhibits almost the same value as at the ground. In contrast, the vertical component (Fig 3 (c) and (d)) shows increasing PFA_v demands with the height of the structure. This confirms the findings of previous studies focusing on the vertical acceleration demand [8-11]. Further the diagrams show that the response of both ground motion sets is very similar in horizontal as well as in vertical direction for the median response as well as the dispersion.

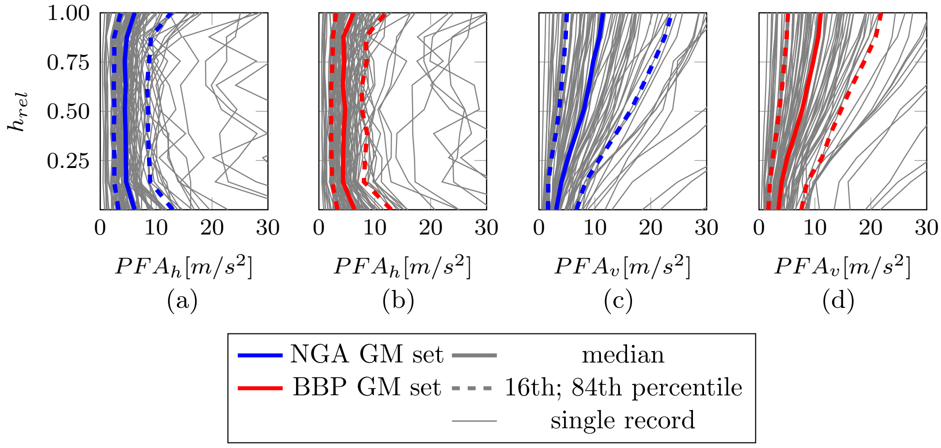

Fig. 3 - Horizontal component ((a) and (b)) and vertical component ((c) and (d)) of the peak floor acceleration response of the exterior column line of both record sets

Next, the medians and dispersions of the horizontal acceleration response of the exterior column line and the vertical acceleration response of the left half of the frame are examined. Hypothesis testing, as introduced by [26], was conducted to assess if there are statistically significant differences between responses to recorded and simulated ground motions. In particular, the two-sided T-test [27] was used for the comparison of the median values and the two-sided F-test for the dispersions. The T-test is typically used to compare the means, but because of the assumption of a log-normally distributed response, it is possible to conduct the test on the median values. Specifically, the logarithmic values of the responses are computed and used for the two-sided T-test, which yields p-values that are valid for the comparison of the median values in normal space. For all conducted hypothesis tests the responses of the recorded NGA ground motion set are considered as the 'ground truth' and it is tested if the responses of the simulated BBP ground motion set show statistically significant differences at the 95% confidence level.

Shown in Fig. 4 are the medians of the absolute PFA demands of the two utilized ground motion sets as well as the 95% confidence level obtained from hypothesis testing. Blue lines represent the response of the recorded NGA ground motion set, red dashed lines the results of the simulated BBP ground motion set, and the black dash dotted lines the rejection region for the 5% significance level. The outcome of the response history analyses has been evaluated at all nodes, but only the results of the left half of the symmetric frame structure are shown and discussed (see Fig. 1 (b)). Since for regular frame models it is sufficient to use one degree of freedom in horizontal direction to assess the behavior of the frame, only the response of the exterior column line (Fig. 4 (a)) is shown, which represents the horizontal response of the whole floor. In contrast, the acceleration response in vertical direction depends on the location of the node in the frame. Hence, the response of the nodes of the left exterior column line is shown in Fig. 4 (b), of the center node of the left bay in Fig. 4 (c), of the left interior column line in Fig. 4 (d), and of the center node of the second bay in Fig. 4 (e).

The largest peak floor acceleration of 11.61 m/s^2 (NGA set) is observed in the center node of the left bay (Fig. 4 (c)). The largest difference of 11.69% between the two median acceleration responses appears in the top floor of the center node of the second bay (Fig. 4 (e)). However, for all evaluated results the medians are very similar and clearly inside the rejection region boundaries for the 5% significance level obtained through hypothesis testing. Therefore, it can be concluded that there are no statistically significant differences in the horizontal and vertical median acceleration response of the two investigated ground motion sets.

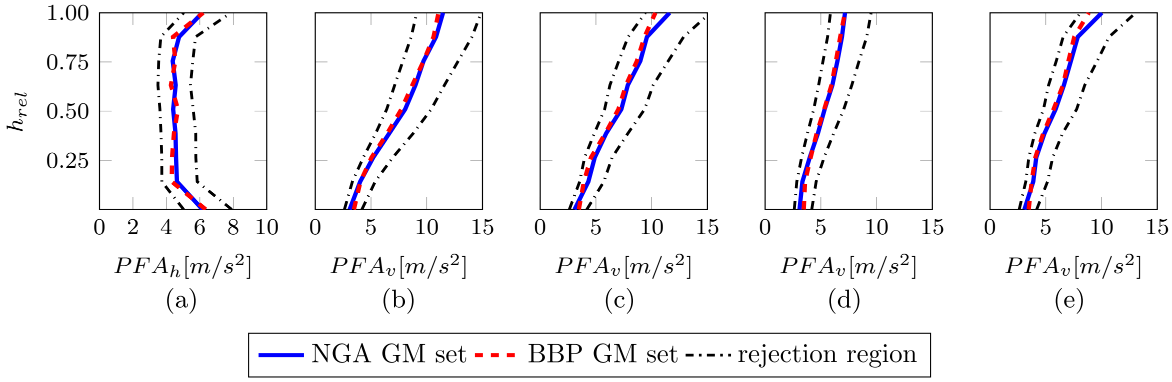

Fig. 4 - Median of the horizontal component (a) and vertical component ((b)-(e)) of the peak floor acceleration response and the rejection region boundaries for the 5% significance level (black lines). (a) Horizontal component of the left exterior column line, vertical component of the (b) left exterior column line, (c) central beam nodes of the left bay, (d) left interior column line, and (e) central beam nodes of the second bay

Since the seismic peak response can be approximated by a log-normal distribution, the record-to-record variability of the absolute horizontal (vertical) peak floor acceleration, PFA_h (PFA_v) can be measured through the dispersion β_{PFA_h} (β_{PFA_v}) [28],

$$\beta_{PFA_h} = \sqrt{\sum_{i=1}^{r} \frac{(\ln(PFA_{h,i}) - \mu_{\ln PFA_h})^2}{r-1}}, \quad \beta_{PFA_v} = \sqrt{\sum_{i=1}^{r} \frac{(\ln(PFA_{v,i}) - \mu_{\ln PFA_v})^2}{r-1}} \tag{1}$$

where r is the number of ground motion records, $\ln(PFA_{h,i})$ ($\ln(PFA_{v,i})$) describes the natural logarithm of the horizontal (vertical) absolute peak floor acceleration demand due to the ith record, and the variable $\mu_{\ln PFA_h}$ ($\mu_{\ln PFA_v}$) represents the mean of $\ln(PFA_{h,i})$ ($\ln(PFA_{v,i})$), $i = 1,\ldots, r$. Shown in Fig. 5 (a) are the dispersions of the horizontal component, while Figs 5 (b)-(e) show dispersions of the vertical component at the considered nodes. Similar to the median response, the dispersion measures of both ground motion sets are very similar and are clearly inside the rejection region boundaries for the 5% significance level yielded by the two-sided F-test. For all nodes, the dispersion is almost constant over the height of the frame in horizontal and vertical direction and exhibits values around 0.80. The maximum dispersion of 0.84 is obtained for the response of the

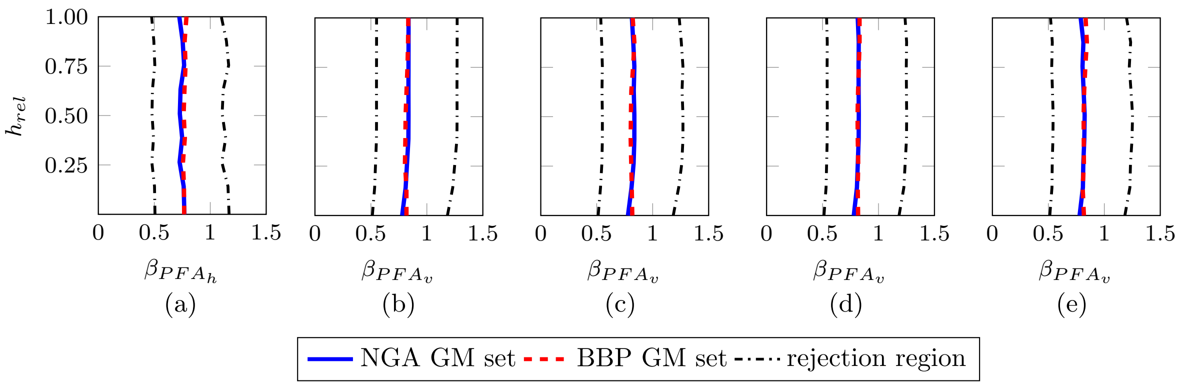

Fig. 5 - Dispersion of the horizontal component (a) and vertical component ((b)-(e)) of the peak floor acceleration response and the rejection region for the 5% significance level (black lines). (a) Horizontal component of the left exterior column line, vertical component of the (b) left exterior column line, (c) central beam nodes of the left bay, (d) left interior column line, and (e) central beam nodes of the second bay

BBP ground motion set in the second to last floor of the center node of the second bay (Fig. 5 (e)). The largest difference between the dispersion of the two ground motion sets appears in the top floor of the horizontal component, where the dispersion of the acceleration response excited by the simulated BBP ground motion set is 8.84% smaller than the dispersion of the recorded NGA ground motion set. The two-sided F-test, represented by the rejection region for the 5% significance level as black dash dotted lines, yields no statistically significant differences between the dispersion of the peak floor acceleration response of the two investigated ground motion sets in horizontal and vertical direction, respectively.

The diagrams in Fig. 6 show the p-values of the conducted hypothesis tests, where the green line represents the horizontal component and the black lines the vertical component. Further, the solid lines show the p-values of the left exterior column line, the dashed lines of the center node of the left bay, the dotted lines of the left interior column line, and the dash dotted lines of the center node of the second bay. As mentioned previously, the response of the recorded NGA ground motion set is considered as the ground truth for these hypothesis tests. Thus, these tests examine if the response of the simulated BBP ground motion set shows statistically significant differences to the recorded NGA ground motion set at the 95% confidence level. The smallest p-value of the T-test (Fig. 6 (a)), which compares the median acceleration response, has a value of 0.18 and is found at the top floor of the center node of the second bay for the vertical component, while the smallest p-value of the F-test (Fig. 6 (b)), used for the dispersions of the acceleration response, of 0.43 appears in the top floor of the horizontal component. In general, the resulting p-values show that none of the responses are near the rejection region, which would mean a p-value of 0.05 or smaller. Thus, it can be concluded that the acceleration response and the corresponding dispersion of the simulated BBP ground motion set show no statistically significant differences to these of the recorded NGA ground motion set at the 95% confidence level.

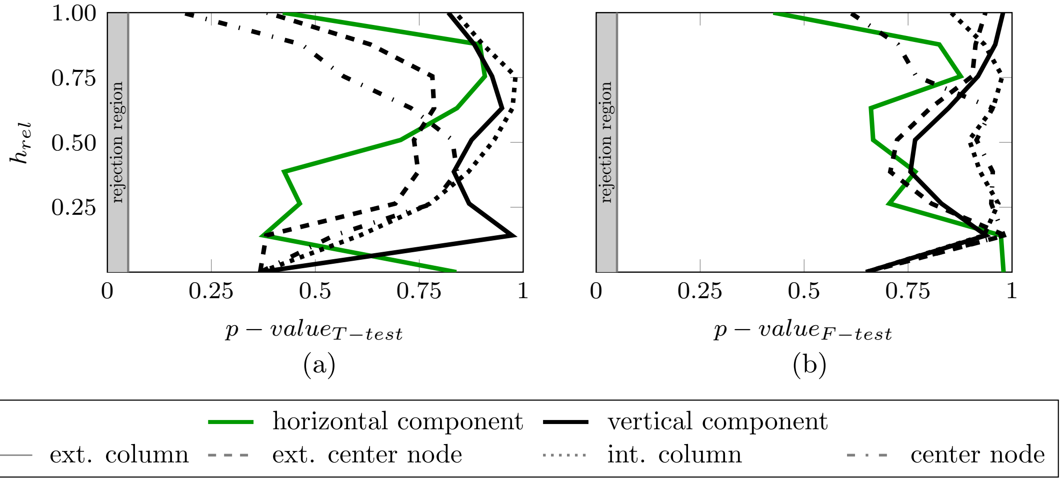

Fig. 6 - P-values from the (a) T-test and the (b) F-test of the absolute acceleration response and the rejection region for the 5% significance level

4.2. Displacement response

This section is concerned with the median displacement response of the 8-story frame model and the corresponding dispersion. The horizontal component is presented in terms of story drift ratios (IDR_h) in Fig 7 (a), while the vertical direction is described by the relative peak floor displacements ($PFD_{v,rel}$) in Fig. 7 (b)-(e) for the considered nodes of each floor. The corresponding dispersions are depicted in Fig. 8. As for the acceleration response, blue lines represent the response of the recorded NGA ground motion set, red lines the response of the simulated BBP ground motion set and the rejection region for the 5% significance level obtained through hypothesis testing, as discussed in the previous section, are depicted as dash dotted black lines.

The horizontal story drift ratio has the largest value in the second to last floor with a value of 0.015 for the response to the recorded NGA ground motion set. The sixth-floor node exhibits the largest difference of 9.44% between the two ground motion sets. In all other stories the story drift ratio has very similar values for both ground motion sets and the medians are well inside the rejection region boundaries for the 95% confidence level for all stories. The vertical component is discussed in terms of $PFD_{v,rel}$ demand. The largest median relative displacement of 1.89 cm appears in the top floor of the exterior column line for the simulated BBP ground motion set, while the largest difference of 11.96% between the two ground motion sets is exhibited in the node of the second to last floor of the exterior column line. It can be seen that both medians of relative displacements are clearly inside the rejection region for the 5% significance level. The median relative displacements are very small what can be attributed to the stiff behavior in vertical direction. But still, as for the acceleration response, an amplification is exhibited for all considered nodes, thus confirming the insight that also the vertical component of the earthquake response should be considered. The similarity between the medians of the two considered ground motion sets, where the recorded NGA ground motion set is considered as the true value, is confirmed by the two-sided T-test. All p-values are larger than 0.5, validating the visual assumption through statistical evaluations by showing no statistically significant difference for the relative displacement response of the two used ground motion sets.

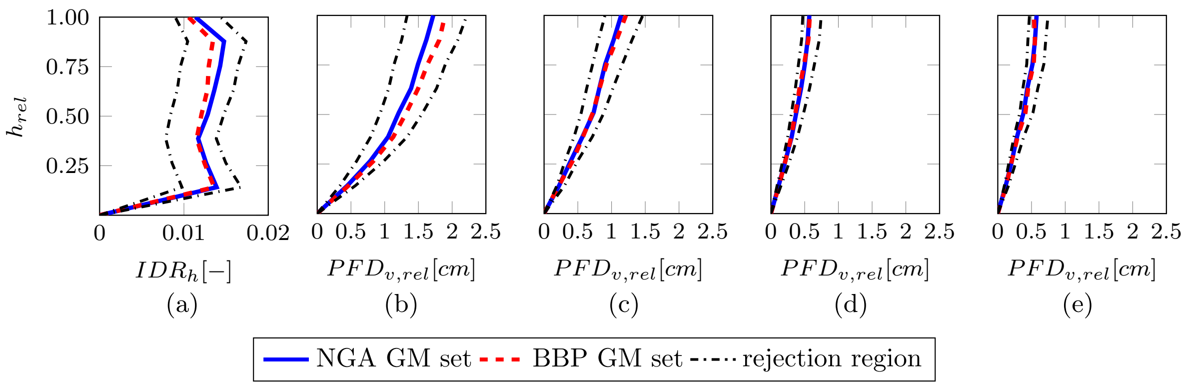

Fig. 7 - Median of the maximum story drifts (a) and the vertical component ((b)-(e)) of the relative peak floor displacement response and the rejection region for the 5% significance level (black lines): (a) Horizontal component of the left exterior column line; vertical component of the (b) left exterior column line, (c) central beam nodes of the left bay, (d) left interior column line, and (e) central beam nodes of the second bay

Fig. 8 displays the dispersion measure for the horizontal story drift ratios (a) and the vertical $PFD_{v,rel}$ (b)-(e). Similar to the acceleration demand, the dispersions for both ground motion sets are very similar. The story drift ratios have larger dispersions with a maximum of 0.97 in the first floor for the response of the simulated BBP ground motion set. The largest difference between the dispersion of the ground motion sets appears in the first floor of the center node of the left bay Fig. 8 (c) and has a value of 9.67%. The visually featured close agreement of the dispersion is also confirmed by the two-sided F-test, which exhibits the smallest p-value of 0.3 for the node in the first story of the center node of the left bay, where the largest difference of the dispersion measure appears. All other p-values are larger than 0.6. Thus, it can be concluded that there is no statistically significant difference for the dispersion of the relative displacement response of the two investigated ground motion sets.

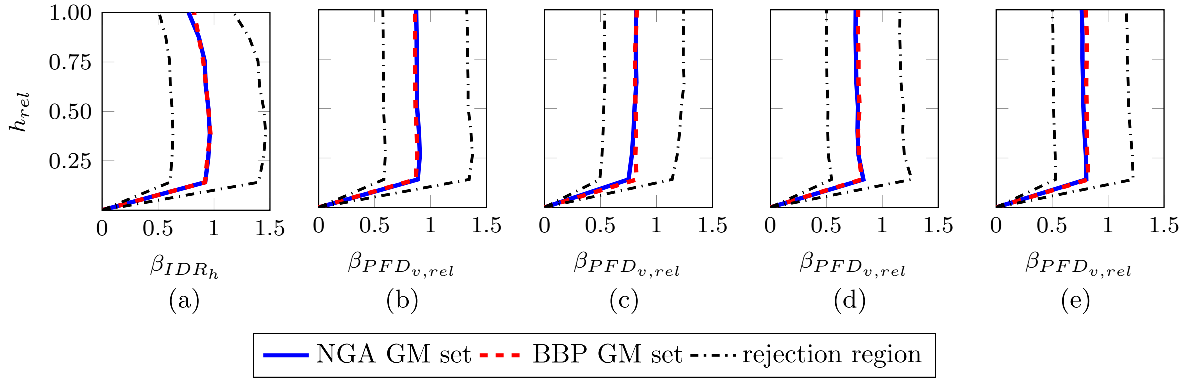

Fig. 8 - Dispersion of the maximum story drifts (a) and the vertical component ((b)-(e)) of the relative peak floor displacement response and the rejection region for the 5% significance level (black lines): (a) Horizontal component of the left exterior column line; vertical component of the (b) left exterior column line, (c) central beam nodes of the left bay, (d) left interior column line, and (e) central beam nodes of the second bay

5. Conclusions

The main objective of this paper is engineering validation of simulated ground motions for use in response history analyses. The novelty of this paper is that not only the horizontal component is considered, but the consideration is also extended to the vertical component of the ground motions. To this end, response history analyses of an 8-story frame were conducted using two sets of spectrum-equivalent recorded and simulated ground motion sets. The recorded ground motions were selected from the PEER NGA database, and the simulated ground motions were obtained from simulations of past earthquakes generated by the SCEC BBP v14.3 implementation of the GP ground motion models. The performed analyses contrast the medians and dispersions of absolute peak floor accelerations, horizontal story drift ratios and vertical relative peak floor displacements. Hypothesis testing was used to test for statistically significant differences between responses to comparable sets of recorded and simulated ground motions.

The conducted analyses indicate that the horizontal as well as the vertical component of the investigated structural responses of simulated and recorded ground motions are very similar. There are no significant differences at the 95% confidence level for the response and the dispersion between the two considered ground motion sets. For the median acceleration and displacement response a maximum difference of 12% is observed, while a maximum difference of 10% is observed for dispersion of displacements.

The observed close agreement between responses is encouraging but not surprising as we only considered the elastic response while the recorded and simulated ground motion sets were developed to have matching spectral accelerations. Important questions to be further investigated include the effect of nonlinear material behavior to evaluate the nonlinear acceleration and displacement response of structures. Moreover, the responses should be investigated at a range of intensities including up to collapse to further assess if the vertical component influences the collapse response and give credence to utilization of simulations in risk based assessments. Another significant issue concerns the variation of the ground motion sets and structural models. Therefore, a study with more ground motion sets and different building and bridge structures should be conducted to get a better understanding of the vertical response using simulated ground motions.

6. References

[1] Papazoglou AJ, Elnashai AS (1996): Analytical and field evidence of the damaging effect of vertical earthquake ground motion. *Earthquake Engineering & Structural Dynamics,* **25** (10), 1109-1137.

[2] Ghobarah A, Elnashai AS (1998): Contribution of vertical ground motion to the damage of RC buildings. *Proceedings of the Eleventh European Conference on Earthquake Engineering*, Paris, France.

[3] Lee RL, Franklin MJ, Bradley BA (2013): Characteristics of vertical ground motions in the Canterbury earthquakes. *New Zealand Society for Earthquake Engineering Annual Conference*, Wellington, New Zealand.

[4] Adam C, Fotiu PA (2000): Dynamic analysis of inelastic primary-secondary systems. *Engineering Structures,* **22** (1), 58-71.

[5] Sankaranarayanan R, Medina RA (2007): Acceleration response modification factors for nonstructural components attached to inelastic moment-resisting frame structures. *Earthquake Engineering & Structural Dynamics*, **36** (14), 2189-2210.

[6] Vukobratovic V, Fajfar P (2017): Code-oriented floor acceleration spectra for building structures. *Bulletin of Earthquake Engineering*, **15** (7), 3013-3026.

[7] Obando JC, Lopez-Garcia D (2018): Inelastic displacement ratios for nonstructural components subjected to floor accelerations. *Journal of Earthquake Engineering*, **22** (4), 569-594.

[8] Moschen L, Medina RA, Adam C (2016): Vertical acceleration demands on column lines of steel moment-resisting frames. *Earthquake Engineering & Structural Dynamics*, **45** (12), 2039-2060.

[9] Francis TC, Hendry BC, Sullivan TJ (2017): Vertical spectral demands on building elements induced by earthquake excitation. *New Zealand Society for Earthquake Engineering Annual Conference*, Wellington, New Zealand.

[10] Gremer N, Adam C, Medina RA, Moschen L (2019): Vertical peak floor accelerations of elastic moment-resisting steel frames. *Bulletin of Earthquake Engineering*, **17** (6), 3233-3254.

[11] Ryan KL, Soroushian S, Maragakis E, Sato E, Sasaki T, Okazaki T (2016): Seismic simulation of an integrated ceiling-partition wall-piping system at E-Defense. I: Three-dimensional structural response and base isolation. *Journal of Structural Engineering*, **142** (2).

[12] Maechling PJ, Silva F, Callaghan S, Jordan TH (2015): SCEC Broadband Platform: system architecture and software implementation: *Seismological Research Letters*, **86** (1), 27-38.

[13] Dreger D, Beroza G, Day S, Goulet C, Jordan T, Spudich P, Stewart J (2015): Validation of the SCEC Broadband Platform V14.3 simulation methods using pseudospectral acceleration data. *Seismological Research Letters*, **86** (1), 39-47.

[14] Bijelić N, Lin T, Deierlein GG (2018): Validation of the SCEC Broadband Platform simulations for tall building risk assessments considering spectral shape and duration of the ground motion. *Earthquake Engineering & Structural Dynamics*, **47** (11), 2233-2251.

[15] Burks LS, Zimmerman RB, Baker JW (2014): Evaluation of hybrid broadband ground motion simulations for response history analysis and design. *Eartquake Spectra*, **31** (3), 1691-1710.

[16] Baker JW, Luco N, Abrahamson NA, Graves RW, Maechling PJ, Olsen KB (2014): Engineering uses of physics-based ground motion simulations. *Proceedings of the 10th National Conference in Earthquake Engineering*, Anchorage, Alaska.

[17] FEMA P-695 (2009): Quantification of Building Seismic Performance Factors. *Federal Emergency Management Agency.* Washington, DC.

[18] NIST GCR 10-917-8 (2010): Evaluation of the FEMA P-695 methodology for quantification of building seismic performance factors. *National Institute of Standards and Technology*.

[19] AISC 358-05 (2005): Prequalified Connections for special and intermediate steel moment frames for seismic applications. *American Institute for Steel Construction*.

[20] AISC 341-05 (2005): Seismic provisions for structural steel buildings. *American Institute for Steel Construction*.

[21] ASCE/SEI 7-05 (2006): Minimum design loads for buildings and other structures. *American Society of Civil Engineers/Structural Engineering Institute.* Reston, VA.

[22] Graves RW, Pitarka A (2010): Broadband ground-motion simulation using a hybrid approach. *Bulletin of the Seismological Society of America*, **100** (5 A), 2095-2123.

[23] Moschen L, Medina RA, Adam C (2019): A ground motion record selection approach based on multi-objective optimization. *Journal of Earthquake Engineering*, **23** (4), 669-687.

[24] FEMA P-1050-1 (2015): Quantification of Building Seismic Performance Factors. *Federal Emergency Management Agency*. Washington, DC.

[25] PEER (2010): PEER Ground Motion Database. *University of California at Berkeley*.

[26] Jayaram N, Shome N (2012): A Statistical Analysis of the Response of Tall Buildings to Recorded and Simulated Ground Motions. *Proceedings of the 15th World Conference on Earthquake Engineering (15WCEE),* Lisbon, Portugal.

[27] DeGroot MH, Schervish MJ (2012): *Probability and Statistics*. Pearson, 4th edition.

[28] Shome N, Cornell CA (1999): Probabilistic seismic demand analysis of nonlinear structures. *RMS Tech Report No. 38*. The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University, Stanford, CA.

