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INFLUENCE OF THE VERTICAL COMPONENT OF EARTHQUAKE ON LARGE SPAN RC BEAMS

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Subject review

Most of the previous studies in the field of earthquake engineering have neglected the effects of vertical ground motion and are usually guided by horizontal motion. The EN1998 proposes action analysis of the vertical acceleration for certain types of elements and their length and their distance from the active fault. In this paper simply supported beams with various spans, 10, 15 and 20 m, are calculated for the action of real earthquakes with different intensities. Two typical cross sections were chosen: "T" cross section and rectangular cross section. The linear and nonlinear material models were used, and all the models were calculated using rigid and elastic supports. Through the combinations of these different spans, cross sections, material models and types of the supports, the influence and importance of the vertical component of the ground motion is estimated. Based on the results obtained it was concluded that there is a need for the application of vertical acceleration in the seismic analysis of these elements.

Keywords: *bending moment, earthquake, rectangular cross section, "T" cross section, vertical acceleration*

Utjecaj vertikalne komponente potresa na AB nosače velikog raspona

Pregledni članak

Dosadašnja su ispitivanja učinaka potresa zanemarivala vertikalno gibanje tla te se uglavnom usmjeravala prema horizontalnoj komponenti. EN1998 daje preporuku analize djelovanja vertikalnog ubrzanja za određene vrste elemenata i njihovih duljina te njihove udaljenosti od aktivnog rasjeda. U radu se analiziraju jednostavno oslonjeni nosači različitih raspona, 10, 15, 20 m te pravokutnog i „T“ poprečnog presjeka. Primijenjena su dva tipa oslanjanja, kruti i elastični ležaj te dva tipa modela materijala, linearni i nelinearni. Nosači su podvrgnuti djelovanju četiri realna potresa različitog intenziteta. Na ovaj se način pratila promjena u momentima savijanja nosača u polovici raspona kako bi se vidio doprinos vertikalnog ubrzanja. Na temelju dobivenih rezultata zaključeno je kako za analizirane nosače ipak postoji potreba primjene vertikalne akceleracije prilikom seizmičke analize.

Ključne riječi: *moment savijanja, potres, pravokutni presjek, "T" presjek, vertikalno ubrzanje*

1 Introduction
Uvod

Most of the previous studies in the field of earthquake engineering have neglected the effects of vertical ground motion and are usually guided by horizontal motion. The main reason for this practice is found in circumstances that engineering structures are intended primarily for vertical load transfer and thereby it is implied that they have sufficient resistance to dynamic forces caused by vertical motion. If the effect of vertical ground motion is included in the analysis, the most common way is to assume the ratio of vertical and horizontal spectra up to 2/3 (UBC 1997, GB50011-2001, EN 1998) [1]. However, observations in recent large intensity earthquakes show that the ratio 2/3 rule is not the best description of the vertical motion. During the 1994 Northridge and 1995 Kobe earthquakes, observations of vertical ground motion presented substantially different behaviour to the horizontal motion. It was noted that at distances greater than 10 km earthquakes with intense vertical component can also occur (Tab. 1) [2].

Data from the Kobe earthquake show that the peak horizontal acceleration was reduced as the waves were travelling from the hypocenter to the surface, while the vertical acceleration significantly increased on the surface, resulting in a ratio of peak vertical and horizontal acceleration on the surface of 1,5 to 2,0. This significantly exceeds the 2/3, a value that is commonly used in engineering practice (Fig. 1).

In recent years, engineers have begun to analyze the combinations of the components because the recent insights call into question the neglecting of the vertical component which can be dominant in the areas near the epicenter. The EN 1998 defines that the vertical component of an

***Table 1** Earthquakes with V/H ratio larger than 2/3 and more than 10 km away from the epicentre*
***Tablica 1.** Potresi omjera V/H većeg od 2/3 udaljeni više od 10 km od epicentra*

State	City	Distance from the epicentre/km	Distance from the fault/km	$a_{V,max}$ / m/s^2	$a_{H,max}$/ m/s^2	V/H
Greece	Thessaloniki	29	17	1,200	1,431	0,84
Montenegro	Bar	16	12	2,486	3,682	0,68
Italy	Calitri	16	14	1,64	1,725	0,95
Italy	Sturno	32	14	2,309	3,168	0,73
Armenia	Gulkasian	36	20	1,353	1,796	0,75
Iran	Rudsar	81	65	0,844	0,952	0,89
Greece	Mataranga	28	33	0,257	0,262	0,98
Turkey	Kocaeli	17	25	2,295	2,905	0,79
Italy	Friuli	27	6	2,624	3,500	0,75
Uzbekistan	Gazli	22	3	12,627	7,068	1,79
Iran	Tabas	52	3	8,229	10,808	0,76
Italy	Nocera Umbra	11	4	4,899	7,454	0,66

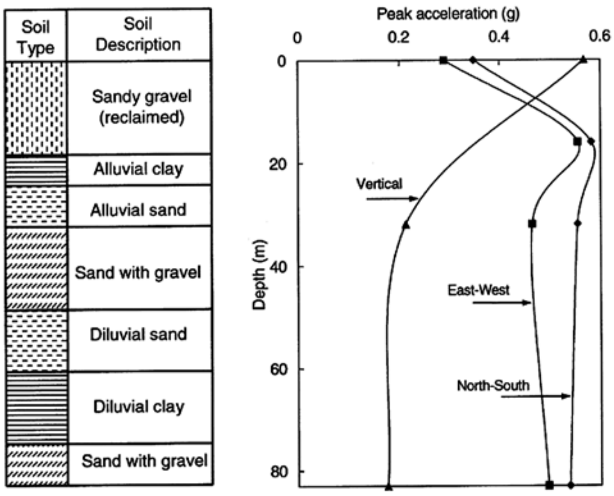


Figure 1 *Variation of the ground acceleration depending on the depth*
Slika 1. *Promjena ubrzanja tla prema površini*

earthquake must be taken into consideration only for locations up to 10 km from the faults that can cause an earthquake greater than magnitude 6,5, and for longer distances may be ignored [3]. In addition to the above recommendation, which is related to the bridges, there are recommendations for other structural elements, such as [4]:

- horizontal or nearly horizontal structural elements with the span of 20 m or more,
- horizontal or nearly horizontal cantilever elements longer than 5 m,
- horizontal or nearly horizontal prestressed elements,
- beams supporting the columns,
- structures with foundation isolation.

There are a large number of studies which showed that the result of unexpected demolition of some structural elements during the earthquake was caused by the vertical component of an earthquake action. Additionally, one of the effects that may occur is the increased P-delta effect. This situation may produce a dominant load combination if it occurs at the same time as the large horizontal and vertical acceleration [5].

2 Description of the calculation models
Opis modela

Simply supported beams with spans of 10 m, 15 m and 20 m were calculated for the action of real earthquakes with different intensities. Two typical cross sections were chosen: "T" cross section and rectangular cross section, each with the geometry regarding to the span. Linear and nonlinear material models were used, and all the models were calculated using rigid and elastic supports. Combining the different spans, cross sections, material models and types of the supports, the influence and importance of the vertical component of the ground motion can be estimated, assuming that the models with the nonlinear material model are the most accurate.

The label of the model consists of five characteristic marks. The first letter denotes the type of the cross section ("T" for T cross sections and "P" for rectangular ones). The following number denotes the length of the span (10 m, 15 m and 20 m). The material model is labelled with "L" (linear) and "N" (nonlinear). "K" denotes the rigid and "E" denotes the elastic support. The last number describes load level (the load which induces 20, 40, 60, 80 and 100 % of $M_{\mathrm{Rd,lim}}$). For example, the label T15LK60 refers to the "T" cross section beam with span length 15 m, linear material model, rigid support and load level which induces 60 % of $M_{\mathrm{Rd,lim}}$ in the middle of the span.

3 Selection of the loads
Odabir opterećenja

3.1 Earthquake action
Potresno opterećenje

For time-history dynamic analysis of structural response, input data must be the complete accelerogram of ground oscillations at the site. The four earthquakes were chosen from the European Strong-Motion Database [6] (Tab. 2). Data from these earthquakes meet the basic requirements for use in the analysis: they are accurate and represent the ground response, records are processed using standard methods, related parameters characterize the source of the earthquake and the path from the epicentre to the hypocenter, the values of parameters are reliable and can be easily set, records are presented in a balanced and easy to use form.

The earthquake records consist of all three components, horizontal components in two perpendicular directions and the vertical component. As this paper is directed towards the observation of the vertical component of an earthquake action, the vertical component is isolated from the overall results of a particular earthquake and analyzed separately (Fig. 2) [7].

3.2 Additional load
Dodatno opterećenje

The models analysed in this paper are loaded with additional linear distributed load. That load comes in reality due to additional dead load (e.g. from non-structural elements or from self-weight of the adjacent structural elements) combined with imposed loads and it has a large influence on dynamic behaviour of the structure [8]. In

Table 2 *Parameters of the selected earthquakes*
Tablica 2. *Parametri korištenih potresa*

Year	Site	Distance from the epicenter	Distance from the fault	Soil	a_x	a_y	a_z	a_z/g
		km			m/s^2			
1979	Bar (Montenegro)	16	12	B	3,682	–3,559	2,486	0,25
1997	Nocera Umbra (Italy)	11	4	A	6,98	–7,454	–4,899	–0,50
1978	Tabas (Iran)	52	3	B	9,087	10,808	8,229	0,84
1976	Gazli (Uzbekistan)	22	3	D	–6,04	–7,068	12,627	1,29

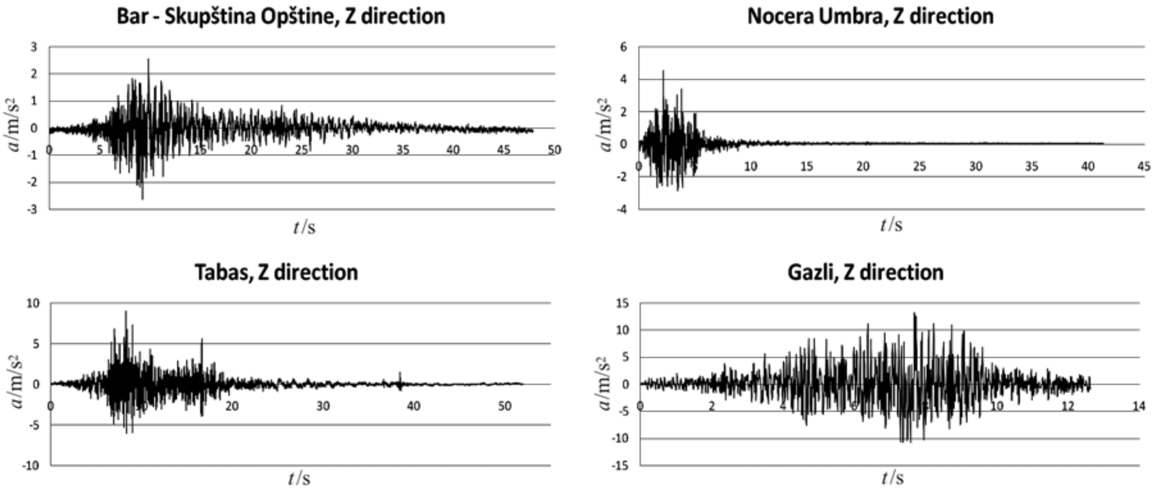


Figure 2 *Accelerograms*
Slika 2. *Akcelerogrami*

Table 3 *Additional load* q_{Ed}/kN/m
Tablica 3. *Dodatna opterećenja* q_{Ed}/kN/m

"T" cross section					
Span/m	q_{Ed} 20 % $M_{Rd,lim}$	q_{Ed} 40 % $M_{Rd,lim}$	q_{Ed} 60 % $M_{Rd,lim}$	q_{Ed} 80 % $M_{Rd,lim}$	q_{Ed} 100 % $M_{Rd,lim}$
10	78,44	169,39	260,33	351,28	442,22
15	75,47	167,94	260,41	352,88	445,35
20	71,74	164,97	258,21	351,45	444,68
Rectangular cross section					
Span /m	q_{Ed} 20 % $M_{Rd,lim}$	q_{Ed} 40 % $M_{Rd,lim}$	q_{Ed} 60 % $M_{Rd,lim}$	q_{Ed} 80 % $M_{Rd,lim}$	q_{Ed} 100 % $M_{Rd,lim}$
10	26,88	63,26	99,63	136,01	172,39
15	22,99	59,98	96,96	133,95	170,94
20	18,79	56,09	93,38	130,68	167,97

order to simulate different levels of serviceability, additional loads of the beams are chosen so that their action, along with the self-weight, causes 20, 40, 60, 80 and 100 % of the limit value of bending moment for the single reinforcement $M_{Rd,lim}$ in the middle of the span. Tab. 3 shows the values of additional load q_{Ed} for each type of the cross section and for each span.

4 Material models
Modeli materijala

For the time-history analysis the two reinforced concrete models were used: the linear and nonlinear composite model [9]. For the nonlinear analysis the Mander-Priestley-Park concrete model was used. This model has a broad application, especially for the circular and rectangular cross-sections and for dynamic and static loads (Fig. 3a). The Giuffre-Menegotto-Pinto steel model was chosen for the reinforcement (Fig. 3b) because it is appropriate for the complex load patterns with significant shifts in direction. Material properties of the concrete and reinforcement used in the model are shown in Tab. 4 and Tab. 5.

Table 4 *Material properties of the concrete*
Tablica 4. *Karakteristike betona*

Class	γ_c	f_{ck}	f_{ct}	E_{cm}	E_c
	kN/m³	N/mm²		N/mm²	
C35/45	24,00	35,00	3,21	33282,28	35033,98

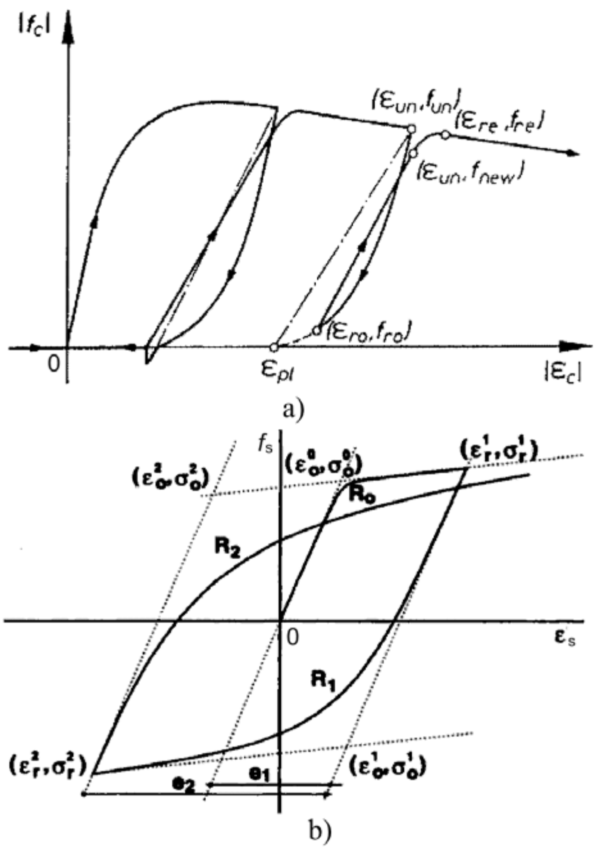


Figure 3 *a) Mander-Priestley-Park concrete model; b) Giuffre-Menegotto-Pinto steel model*
Slika 3. *a) Mander, Priestley, Park model betona; b) Giuffre-Menegotto-Pinto model čelika*

Table 5 *Material properties of the reinforcement steel*
Tablica 5. *Karakteristike armature*

Steel	γ_s	f_{yk}	f_u	E_s
	kN/m^3	N/mm^2		N/mm^2
B500B	78,50	500,00	540,00	210000,00

4.1 Supports
Ležajevi

The type of the bearings may influence the dynamic response of the structure. In this paper two types of the bearings were used: most common rigid support and elastomeric bearing. Elastomeric bearings are deformable devices which are used for load transfer from one structural element to another. In this research the Type 1 non-slip-resistant elastomeric bearing was used. Properties of the bearing (Tab. 6) were obtained from the laboratory testing conducted at Institut IGH d.d. Zagreb [10]. Fig. 4 shows force – deflection diagram for the chosen bearing.

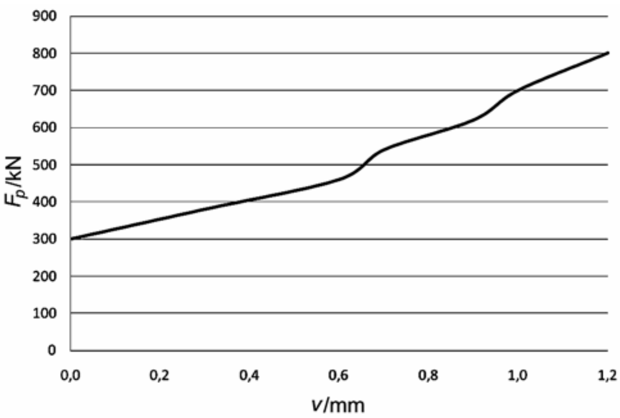


Figure 4 *Force-deflection diagram of the elastomeric bearing test* [10]
Slika 4. *Dijagram ovisnosti sila-progib* [10]

Table 6 *Elastomeric bearing properties*
Tablica 6. *Parametri ležaja*

Elastomeric bearing	Width	Length	Height	Area	Thickness of the elastomer	Number of the elastomer layers	Thickness of the elastomer layers	Thickness of the steel sheet
	a	*b*	*d*	*A*	*T*	*n*	*t*	*s*
	mm			mm^2	mm		mm	
Type 1	200	300	41	60000	29	3	8	3

Compressive stiffness (Tab. 7) of the bearing is calculated as (F_z - vertical force, v_z - deflection):

$$c_c = \frac{F_{z2} - F_{z1}}{\nu_{z2} - \nu_{z1}} \tag{1}$$

Table 7 *Compressive stiffness of the bearing*
Tablica 7. *Tlačna krutost ležaja*

Bearing label	F_{z1}	F_{z2}	v_{z1}	v_{z2}	*c*
	kN		mm		kN/mm
EL-T-002/07/1-4	300	800	0,0	1,2	416,67

Table 8 *Cross section geometry*
Tablica 8. *Geometrija presjeka*

Cross section type	Span	Height of the cross section mm	Width mm	Width of the flange mm	Height of the flange mm
"T"	10	95	40	100	20
	15	140			
	20	185			
RECTANGULAR	10	95	40		
	15	140			
	20	185			

5 Cross section geometry
Geometrija presjeka

Two typical cross sections types are chosen for this research: "T" cross section and rectangular cross section (Fig. 5). The geometry of the cross sections (Tab. 8) is chosen according to EN 1992 Part 1-1 so their span/depth ratio is limited (clause 7.4.2). For each cross section type and load level, the required and provided reinforcement was calculated (Tables 9 and 10) [11].

6 Analysis of the results
Analiza rezultata

From the data for the four chosen earthquakes the vertical component is isolated and applied to the beams. The effects of the vertical component of the ground motion are investigated, combining different spans, material models and supports. The analysis was conducted using Seismosoft software (SeismoStruct 5.0.0., build: 35). The results are shown below.

Increase is observed in bending moments of the beams resting on elastic bearings, regardless of the range, load and earthquake. Increase is also noted in bending moments of the beams which are modelled with the linear material model, compared to nonlinear material model. The smallest increase of bending moments is observed with the vertical acceleration of Nocera Umbra earthquake, despite the fact that vertical acceleration is greater than the vertical acceleration of the Bar earthquake. The reason for this is in a different frequency range of earthquakes. The greatest increase is observed with the vertical acceleration of the earthquake Gazli.

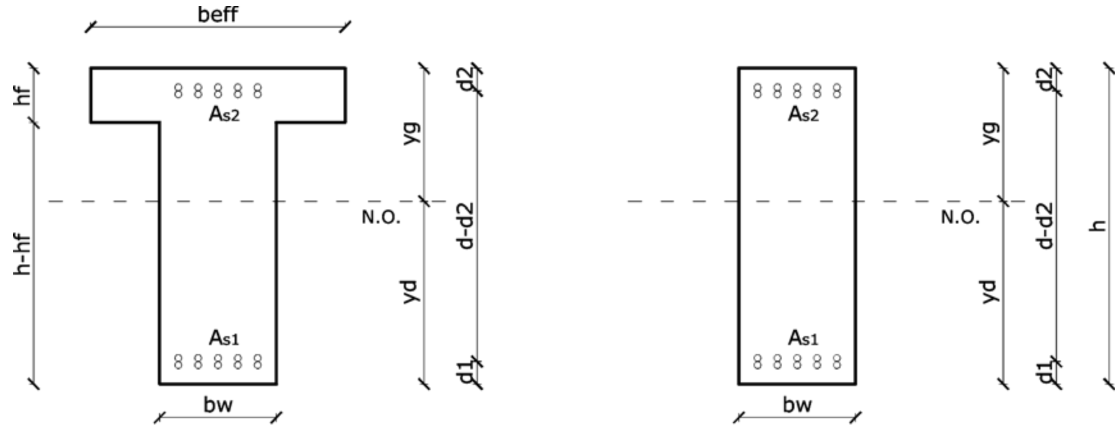


Figure 5 *Cross sections of the beams*
Slika 5. *Poprečni presjeci greda*

Table 9 *Cross sectional area of reinforcement for "T" cross section*
Tablica 9. *Ploštine armature za "T" presjeke*

Reinforcement ratio/ρ %	Additional Load % $M_{\mathrm{Rd,lim}}$	Required cross sectional area of reinforcement A_{s1}/cm^2	Number of bars Φ 32 Required n	Number of bars Φ 32 Provided n_{prov}	Provided cross sectional area of reinforcement A_{s1}/cm^2
"T" cross section, *l*=10 m, *h*=95 cm					
0,63	20	31,35	3,9	4	32,16
1,30	40	64,95	8,1	8	64,32
2,09	60	104,61	13,0	13	104,52
3,86	80	154,04/25,95	19,2/3,2	20/4	160,8/32,16
4,00	100	200,13	24,9	25	201,00
"T" cross section, *l*=15 m, *h*=140 cm					
0,70	20	47,41	5,9	6	48,24
1,44	40	98,24	12,2	12	96,48
2,67	60	181,62	22,6	23	184,92
4,02	80	231,83/38,10	28,8/4,7	29/5	233,16/40,2
4,45	100	302,70	37,6	38	305,52
"T" cross section, *l*=20 m, *h*=185 cm					
0,74	20	63,48	7,9	8	64,32
1,53	40	131,53	16,4	16	128,64
2,83	60	243,17	30,2	31	249,24
4,39	80	306,02/62,85	38,1/7,8	39/8	313,56/64,32
4,71	100	405,28	50,4	51	410,04

6.1 Bending moments for "T" cross section
Dijagrami momenata savijanja za "T" presjek

For the beams with "T" cross section and span of 10 m, increase of bending moments ranges from 9,01 % to 76,89 % (Fig. 6), for the span of 15 m increase ranges from 6,52 % to 76,11 % (Fig. 7) and for span of 20 m increase ranges from 3,86 % to 74,11 % (Fig. 8), compared to the static bending moment.

Comparing the results obtained from the beam models with "T" cross section resting on rigid and elastic bearings, the following differences were observed:

- For the beams resting on rigid bearings and for all load levels, increase of bending moments for the models with linear material model ranges from: for span of 10 m between 1,94 % and 41,03 %, for span of 15 m between 2,07 % and 45,61 % and for span of 20 m between 2,15 % and 47,27 %, compared to the values obtained for models with a nonlinear material model,
- For beams resting on elastic bearings and for all load levels, increase of bending moments for models with a linear material model, ranges from: for span of 10 m between 2,83 % and 41,60 %, for span of 15 m between 2,55 % and 54,31 %, for span of 20 m between 2,70 % and 57,19 % compared to the values obtained for models with a nonlinear material model.

Comparing the results obtained from beam models with "T" cross section, modelled with linear and nonlinear material models, the following differences were observed:

- For beams with linear material model for all load levels, supported on elastic bearings, increase of bending moments ranges from: for span of 10 m between 0,07 % and 7,32 %, for span of 15 m between 1,08 % and 6,44 % and for span of 20 m between 1,23 % and 6,64 % compared to the values obtained on the models supported with rigid bearings,
- For beams with the nonlinear material model for all load levels, increase of bending moments of the models on elastic bearings, ranges from: for span of 10 m between 0,02 % and 2,91 %, for span of 15 m between 0,10 % and 1,87 % and for span of 20 m between 0,04 % and 12,53 % compared to the values obtained on the models supported with rigid bearings.

Table 10 *Cross sectional area of reinforcement for rectangular cross section*
Tablica 10. *Ploštine armature za pravokutne presjeke*

Reinforcement Ratio/ρ %	Additional Load % $M_{Rd,lim}$	Required cross sectional area of reinforcement A_{s1}/cm^2	Number of required bars Φ 32		Provided cross sectional area of reinforcement A_{s1}/cm^2
			n	n_{od}	
Rectangular cross section, l=10 m, h=95 cm					
0,33	20	12,54	1,6	2	16,08
0,68	40	25,98	3,2	4	32,16
1,08	60	41,17	5,1	5	40,20
1,56	80	59,12	7,4	8	64,32
2,11	100	80,05	10,0	10	80,05
Rectangular cross section, l=15 m, h=140 cm					
0,34	20	18,97	2,4	3	24,12
0,70	40	39,30	4,9	5	40,20
1,11	60	62,27	7,7	8	64,32
1,60	80	89,41	11,1	11	88,44
2,16	100	121,08	15,1	15	120,60
Rectangular cross section, l=20 m, h=185 cm					
0,34	20	25,39	3,2	4	32,16
0,71	40	52,61	6,5	7	56,28
1,13	60	83,37	10,4	11	88,44
1,62	80	119,71	14,9	15	120,60
2,19	100	162,11	20,2	20	160,8

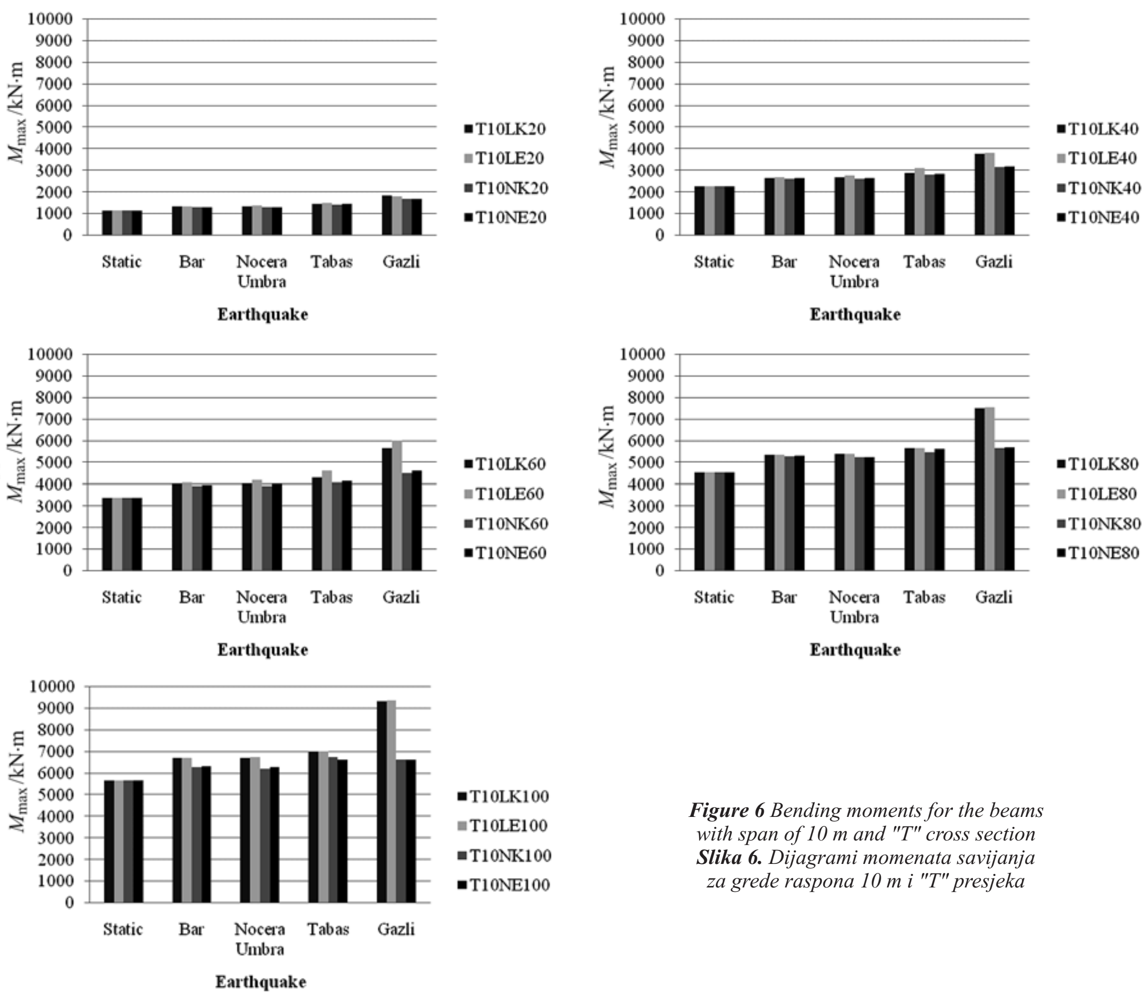
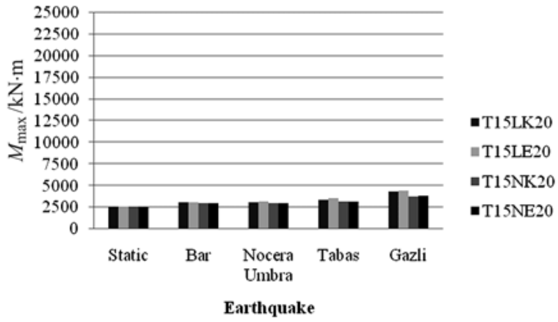
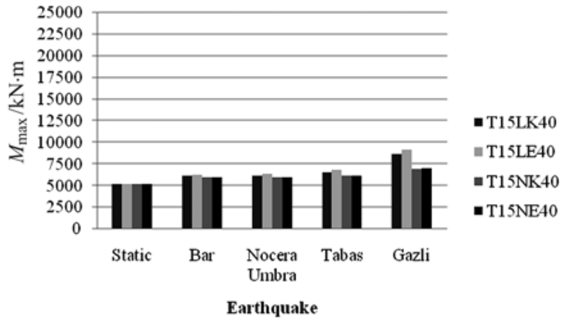
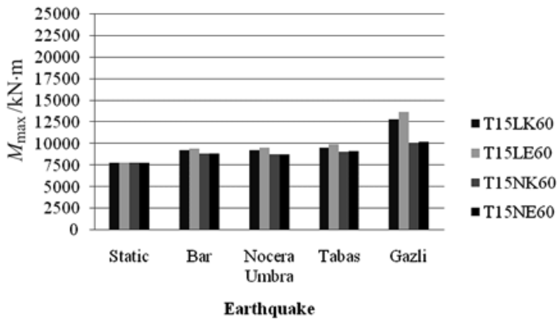
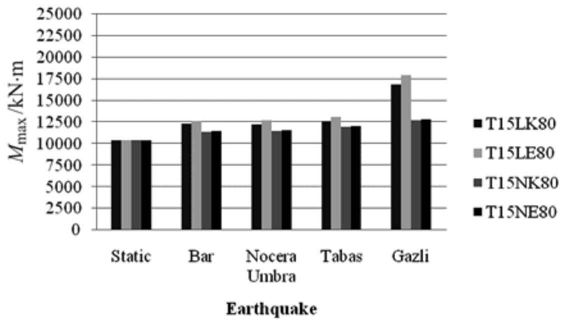


Figure 6 *Bending moments for the beams with span of 10 m and "T" cross section*
Slika 6. *Dijagrami momenata savijanja za grede raspona 10 m i "T" presjeka*









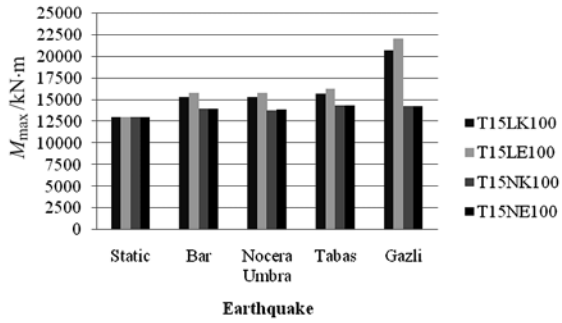
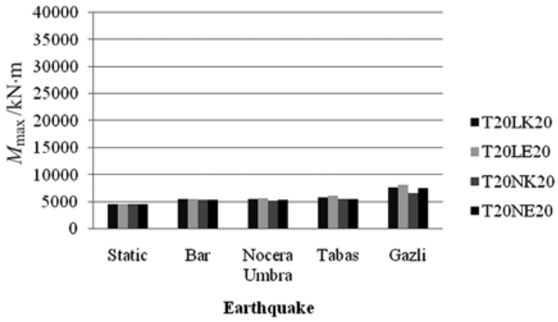
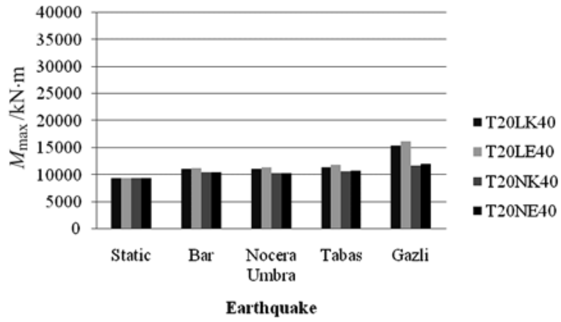
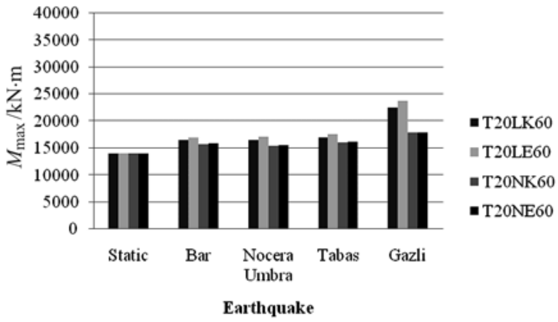
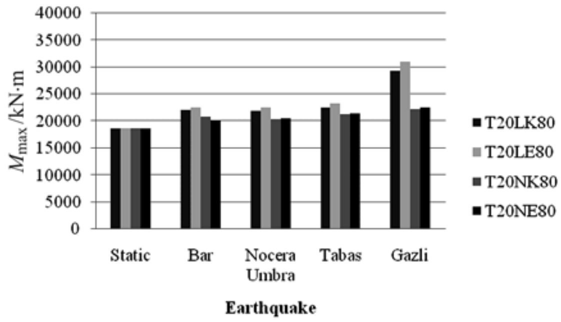


***Figure** 7 Bending moments for the beams with span of 15 m and "T" cross section*
***Slika 7.** Dijagrami momenata savijanja za grede raspona 15 m i "T" presjeka*









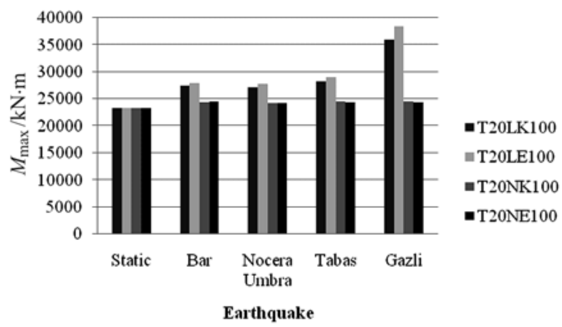
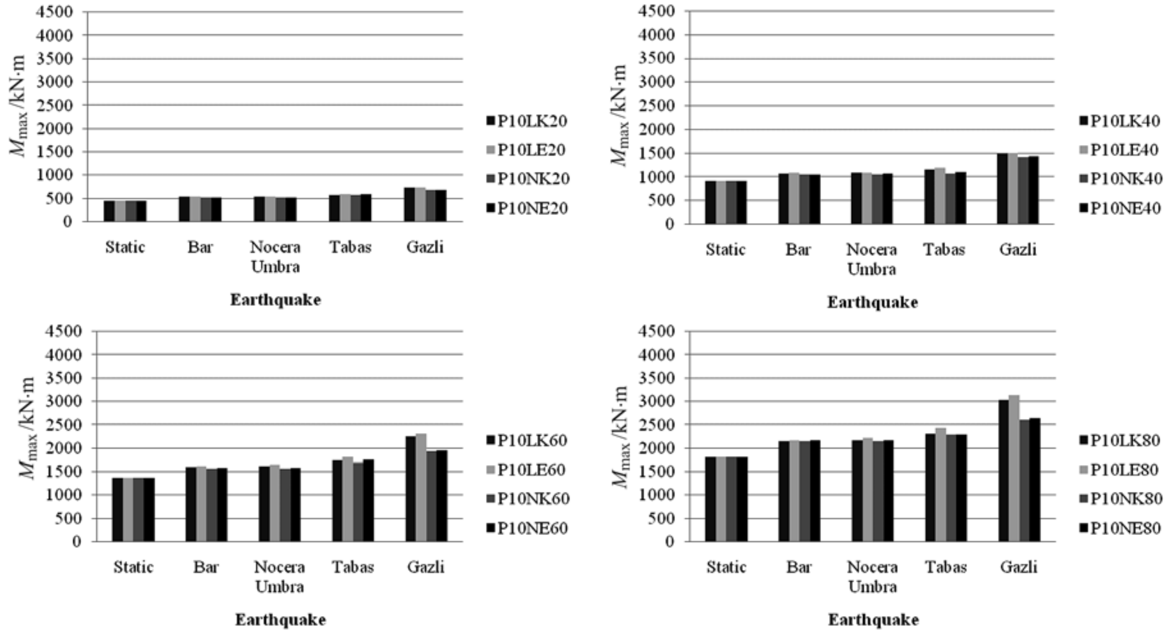


***Figure 8** Bending moments for the beams with span of 20 m and "T" cross section*
***Slika 8.** Dijagrami momenata savijanja za grede raspona 20 m i "T" presjeka*



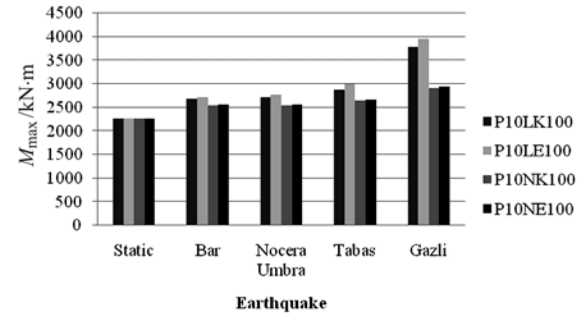
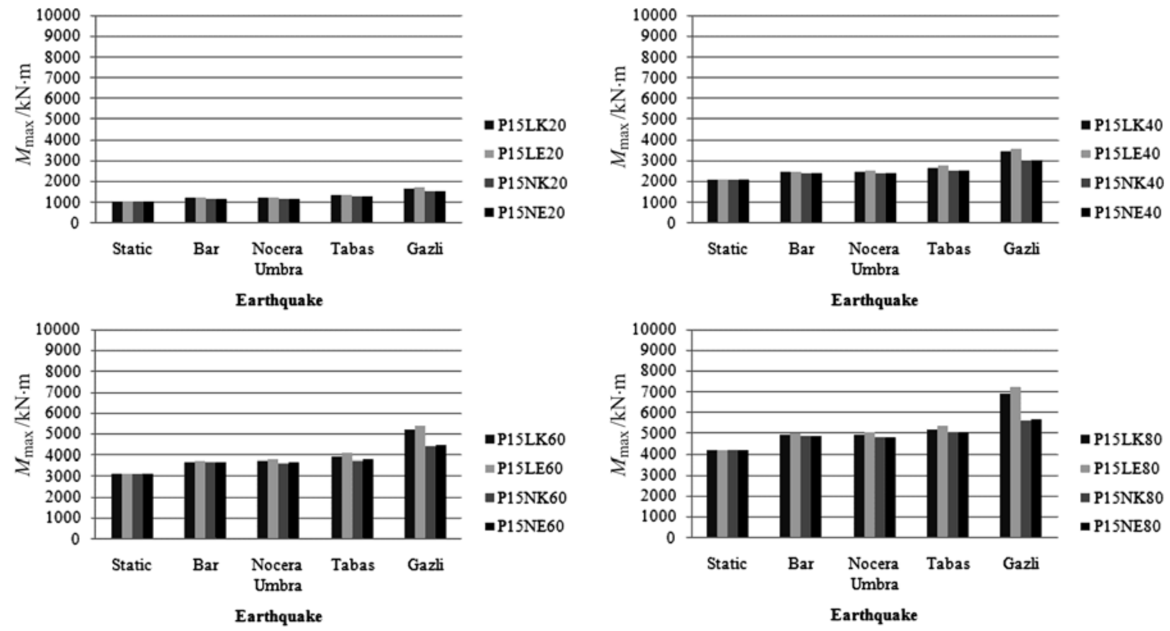


Figure 9 *Bending moments for the beams with span of 10 m and rectangular cross section*
Slika 9. *Dijagrami momenata savijanja za grede raspona 10 m i pravokutnog presjeka*



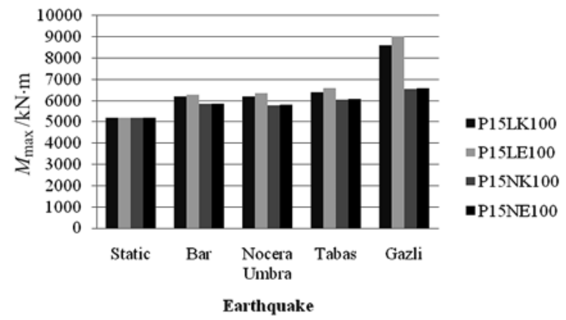


Figure 10 *Bending moments for the beams with span of 15 m and rectangular cross section*
Slika 10. *Dijagrami momenata savijanja za grede raspona 15 m i pravokutnog presjeka*

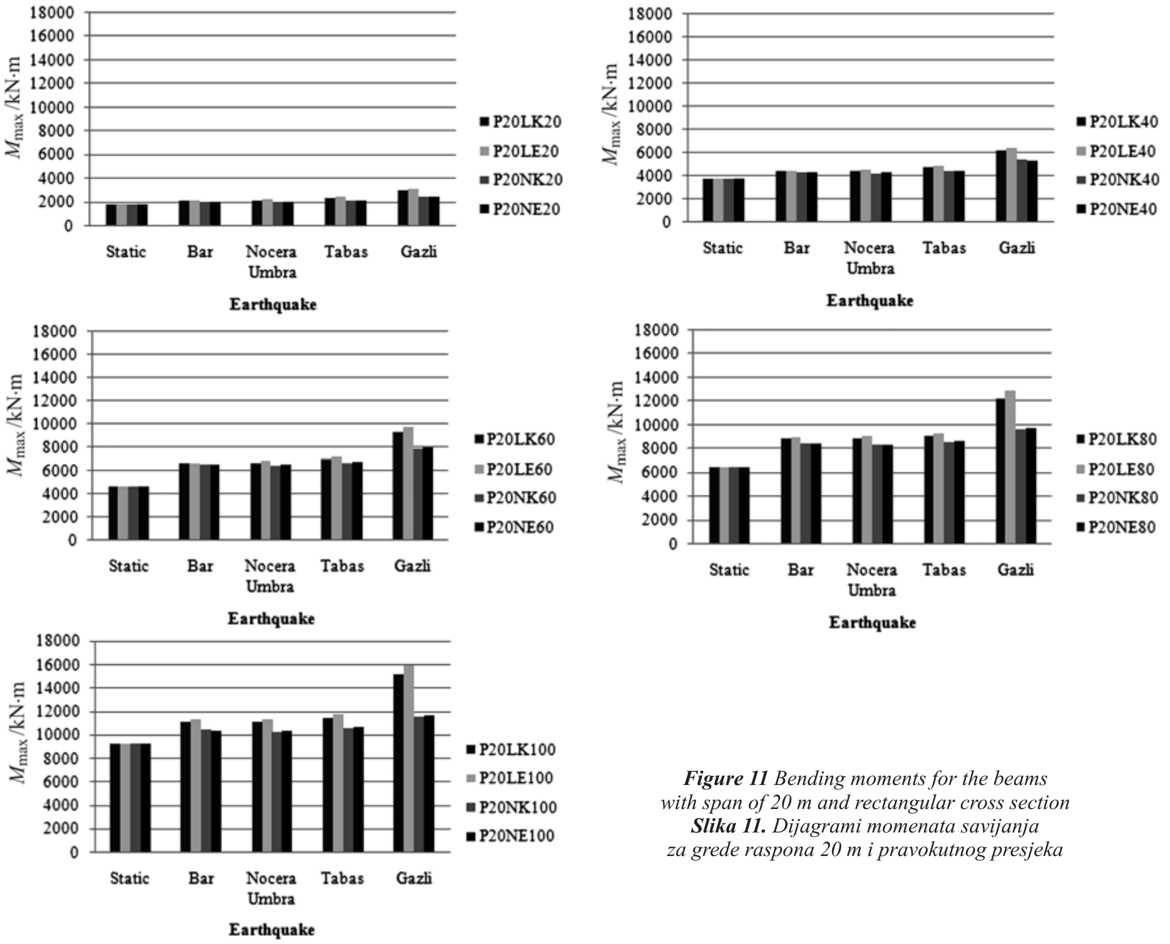


***Figure 11** Bending moments for the beams with span of 20 m and rectangular cross section*
***Slika 11.** Dijagrami momenata savijanja za grede raspona 20 m i pravokutnog presjeka*

6.2 Bending moments for rectangular cross section
Dijagrami momenata savijanja za pravokutni presjek

For beams of rectangular cross section and span of 10 m, increase of bending moments ranges from 11,84 % to 73,92 % (Fig. 9), for span of 15 m increase ranges from 10,92 % to 74,05 % (Fig. 10) and for span of 20 m increase ranges from 10,52 % to 108,02 % (Fig. 11), compared to the static bending moment. These results are obtained from all used earthquakes.

Comparing the results obtained from beam models with rectangular cross section resting on rigid and elastic bearings, the following differences were observed:

- For beams resting on rigid bearings for all load levels, increase of bending moments, for models with a linear material model, ranges from: for span of 10 m between 0,15 % and 30,07 %, for span of 15 m between 0,78 % and 31,89 % and for span of 20 m between 1,11 % and 31,05 %, compared to the values obtained for models with a nonlinear material model,
- For beams resting on elastic bearings for all load levels, increase of bending moments, for models with a linear material model, ranges from: for span of 10 m between 0,21 % and 34,16 %, for span of 15 m between 1,31 % and 36,57 % and for span of 20 m between 1,87 % and 35,71 %, compared to the values obtained for models with a nonlinear model of the material.

Comparing the results obtained from beam models with rectangular cross-section modelled with linear and nonlinear material model, the following differences were observed:

- For beams with linear material model for all load levels, supported on elastic bearings, increase of bending moments ranges from: for beams with span of 10 m between 0,57 % and 4,87 %, for beams with span of 15 m between 0,26 % and 4,60 % and for beams with span of 20 m between 0,94 % and 4,52 %, compared to the values obtained on the models supported on rigid bearings,
- For beams with nonlinear material model for all load levels, supported on elastic bearings, increase of bending moments ranges from: for beams with span of 10 m between 0,03 % and 3,94 %, for beams with span of 15 m between 0,21 % and 1,50 % and for beams with span of 20 m between 0,30 % and 1,57 %, compared to the values obtained on the models supported on rigid bearings.

7 Conclusions
Zaključak

Although most of the regulations do not emphasize the importance of the vertical earthquake component, the results obtained show that it is necessary to consider its influence on the behaviour of structures before it is completely ignored. The regulations refer to its importance in the distances less than 10 km of active faults, but as we showed in Tab. 1 significant vertical components of earthquakes may appear at large distances, which can cause greater damages than expected.

The analysis of the results led to the following conclusions:

- Earthquakes with a high-intensity vertical component can increase bending moments up to 109 % compared to static bending moment, which is the case for P20LE60 model for the Gazli earthquake
- Higher sensitivity of the rectangular cross section was observed compared to the "T" cross section, as a result of smaller area of the compression zone
- Generally, beams on elastic supports have an increased bending moment compared to models on rigid supports, up to 4,87 % for beams for rectangular cross section and 12,53 % for "T" cross section. That increase is larger for beams using the linear material model and can be attributed to inertial forces due to compressibility of the elastomer. Beams using the nonlinear material model show an insignificant increase in bending moment due to energy dissipation during vibrations.
- All the models show regularity in the dependency between bending moments and the span
- For the low and medium seismicity zones the differences in bending moments between the beams with linear and nonlinear material models are small, up to 14,40 % for beams for rectangular cross section and 18,60 % for "T" cross section. Therefore it is reasonable and safe to apply a linear material model within these zones.
- In the high seismicity areas, bending moments are much smaller, up to 36,57 % for beams for rectangular cross section and 57,19 % for "T" cross section, when applying the nonlinear material model due to energy dissipation and plastification of the cross section. Using the linear material model in these cases leads to oversizing of the RC element.

According to the EN 1998, the vertical component may be neglected for elements with spans less than 20 m. This analysis clearly shows the significant increase in bending moments due to vertical earthquake component, even in spans up to 20 m. From this we can conclude that the vertical earthquake component should be carefully investigated, regardless of the distance from the fault.

7 Literature
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