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STORY YIELD STRENGTHS FOR ELASTOPLASTIC MDOF SYSTEMS

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SUMMARY

Most seismic building codes procedures specified formulas for the computation of base shear for a certain structure (as function of its fundamental period) and the distribution of lateral forces over the height of the building. This distribution of lateral forces is determined from the base shear in accordance with formulas implying that buildings are typically considered to respond in a simplified first mode shape. Many efforts have been made to obtain the base shear a building should have to get a good seismic performance, but the distribution of this strength over the height keeps being the same. The study is based on the computation of story shear strength for ten steel moment resisting frame buildings undergoing different level of inelastic deformation when subjected to 46 earthquake ground motions. The ground motions used were recorded on different soil conditions corresponding to firm (site classes A, B, C and D according to the 1997 NEHRP Provisions). The influence of three parameters is studied: a) the level of inelastic deformation in the building; b) number of stories; c) the fundamental period of vibration of the building. Results indicate that a first mode shear distribution can be applied to low level structures and mid level rigid systems (high frecuency structures). For mid- to high level buildings the shear distribution shows the influence of high level modes for elastic cases and for inelastic case the distribution changes depending the height of the building and the level of ductility. The fundamental period has no influence on the story shear distribution and a direct comparison between the distribution over the height of the dynamic story shear distribution and design story shears (UBC code) was made.

INTRODUCTION

Most seismic codes require the structure be designed to resist specified shear seismic forces due to the seismicity of the region and properties of the structure. There are three type of analysis to estimate design forces generated by seismic forces for Multi-Degree-of-Freedom (MDOF) systems: Dynamic inelastic time-history analysis, modal superposition and equivalent lateral force or static analysis. The latter procedure is the most popular among designers because of its simplicity; this method is based on the estimation of the fundamental natural period of the MDOF, the seismic design base shear is calculated and

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component forces obtained from the base shear transform in lateral forces distributed over the height of the structure. Finally the structure is analyzed under this seismic lateral forces, structural elements are design to resist seismic actions and structural displacements are estimated. The distribution of base shear over the height of the building considered that the system would respond in a simplified first-mode shape. Some codes (i.e. UBC-94 [4], NEHRP [1]), consider that small and medium buildings (less than 10 stories high) present a linear first-mode shape; for structures higher than 10 stories high there is a concentration of lateral force at the roof-level to account the influence of higher modes in the response of the structure, increasing shears in upper levels.

In general this approach has been applied in hundreds of buildings presenting a good behavior when subjected to an earthquake, but it is not kwon if those buildings have not develop higher demands of ductility in upper stories than expected. Ductility demands are considered by the codes as it is calculated the base shear and the lateral forces distributed in each story consider that the maximum ductility demand would be present in the first story, could that be always true?

The aim of this study is to understand the distribution of the base shear over the height of buildings and investigate the influence of the displacement ductility demand, number of stories and fundamental period of the MDOF studied in this shear distribution. Finally a direct comparison between the dynamic shear distribution over the height and the design story shears for each story (UBC-1994) [4] is made.

STRUCTURAL MODELS, GROUND MOTIONS AND METHOD OF ANALYSIS

Structural Models

Ten steel moment-resisting frame (SMRF) buildings with four, eight, twelve, sixteen and twenty stories high were considered in this study. The structural plan is the same for all buildings, as shown in Figure 1. All buildings were assumed to have a non-uniform lateral stiffness distribution and a uniform mass distribution over their height. Steel members design was evaluated using the lateral load distribution according to UBC-1994 [4]. Member stiffness were determined in order to obtain representative fundamental periods of vibration for each building from those obtained for earthquake records of instrumented existing SMRF buildings [3]. Each section was selected according to resistance design of strong-column/weak-beam behavior; however, hinge formation at columns can be expected and ductility demands could change along the height of the buildings.

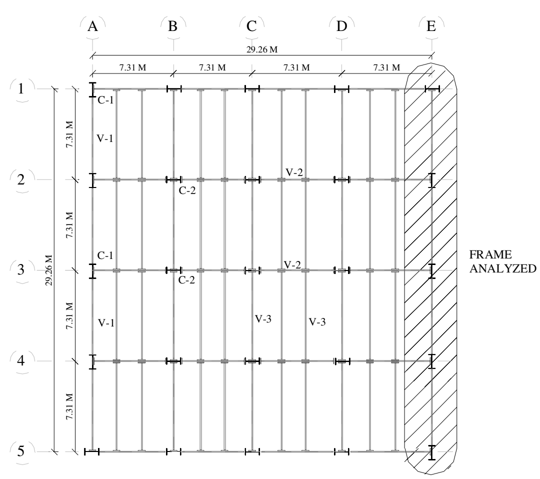


Figure 1. Structural Plan View of the multi-story buildings used in this study.

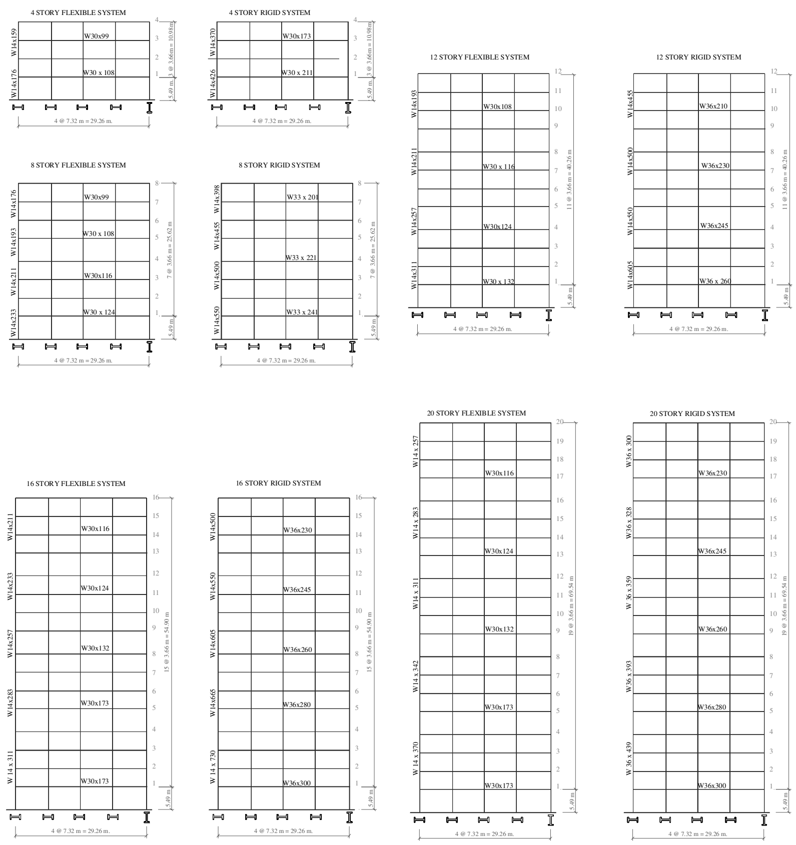


Figure 2. Frames Analyzed for flexible and rigid buildings.

In Figure 2 are presented the frames analyzed for each building; each frame shows the steel section for beams and columns for different levels. In Table 1 are presented the dynamic characteristics for each system studied, such as the fundamental period of vibration, the first mode effective modal mass normalized by the total mass of the system and the ratio of the base shear yield strength to the weight of the structure. This last two ratios were calculated with a pushover analysis with an elasto-plastic behavior.

Table 1. Dynamic properties of studied MDOF systems.

System	T_1 (s)	M_1 / M_T	V_{by} / W
4 story flexible	1.27	0.94	0.30
4 story rigid	0.77	0.93	0.86
8 story flexible	2.02	0.88	0.21
8 story rigid	1.19	0.88	0.42
12 story flexible	2.68	0.84	0.15
12 story rigid	1.63	0.84	0.33
16 story flexible	3.26	0.82	0.15
16 story rigid	1.97	0.83	0.33
20 story flexible	3.84	0.81	0.13
20 story rigid	2.37	0.78	0.26

Ground Motions.
All Frames analyzed were subjected to 46 strong ground motions records as listed in Table 2.

Table 2. Set of ground motions recorded on rock and firm sites.

Earthquake	Station Name Location	Epicentral distance	Magnitud M_s	Components and Maximum Accelerations				Site class NEHRP
Loma Prieta	Gilroy 1, Gavillan Coll.	10.90	7.1	90	433.6	360	426.6	A,B
Northridge	Los Angeles, Gritfith Park	24.50	6.8	360	162.9	270	282.1	A,B
Whittier	Los Angeles, Gritfith Park	22.30	6.1	0	-133.8	360	-121.4	A,B
Loma Prieta	San Francisco, Cliff House	87.40	7.1	0	-73.1	90	-105.7	A,B
Loma Prieta	San Francisco, Pacific Heights	81.20	7.1	270	60.2	360	46.3	A,B
Loma Prieta	Point Bonita	88.10	7.1	297	71.4	207	69.9	A,B
San Fernando	Los Angeles, Gritfith Park	21.00	6.5	180	183.7	270	173.7	A,B
Whittier	Garvey Reservoir Abutment	11.30	6.1	60	-367.1	330	-468.2	C
Northridge	Castaic Old Ridge Route	38.62	7.5	360	504.2	90	557.1	C
San Fernando	Glemdale, 633 E. Broadway	18.00	6.5	110	265.7	200	-209.1	C
Loma Prieta	Corralitos, Eureka Canyon	2.20	7.1	90	469.4	360	617.7	C
Loma Prieta	Saratoga, Aloha Ave.	12.40	7.1	90	316.2	0	494.5	C
Loma Prieta	Woodside, Fire Station	39.40	7.1	90	79.7	0	79.5	C
Kern County	Santa Barbara, Courthouse	85.00	7.7	42	-87.8	132	128.6	C
Imperial	El Centro, Parachute Test	15.00	6.8	225	106.9	315	200.2	C
Kern County	Los Angeles, Hollywood	107.00	7.7	90	41.2	180	-58.1	D
Loma Prieta	Gilroy 2, Hwy 101 Bolsa	12.60	7.1	90	316.3	0	394.2	D
Northridge	Los Angeles, Hollywood	22.53	6.8	360	381.4	90	227.0	D
San Fernando	Los Angeles, Hollywood	23.00	6.5	90	-207.0	180	167.3	D
Whittier	Vernon, Cmd Terminal	11.10	6.1	7	-267.3	277	-239.9	D
Imperial	El Centro #4, Anderson Road	7.00	6.8	140	483.6	230	-349.7	D
Imperial	El Centro #7, Imperial Valley	1.00	6.8	230	453.7	140	326.8	D
Imperial	El Centro #6, 551 Huston	1.00	6.8	140	-368.7	230	-428.1	D

recorded on different soil conditions corresponding to rock and firm sites corresponding to site classes A,B, C and D according to NEHRP Provisions,1997 [1].

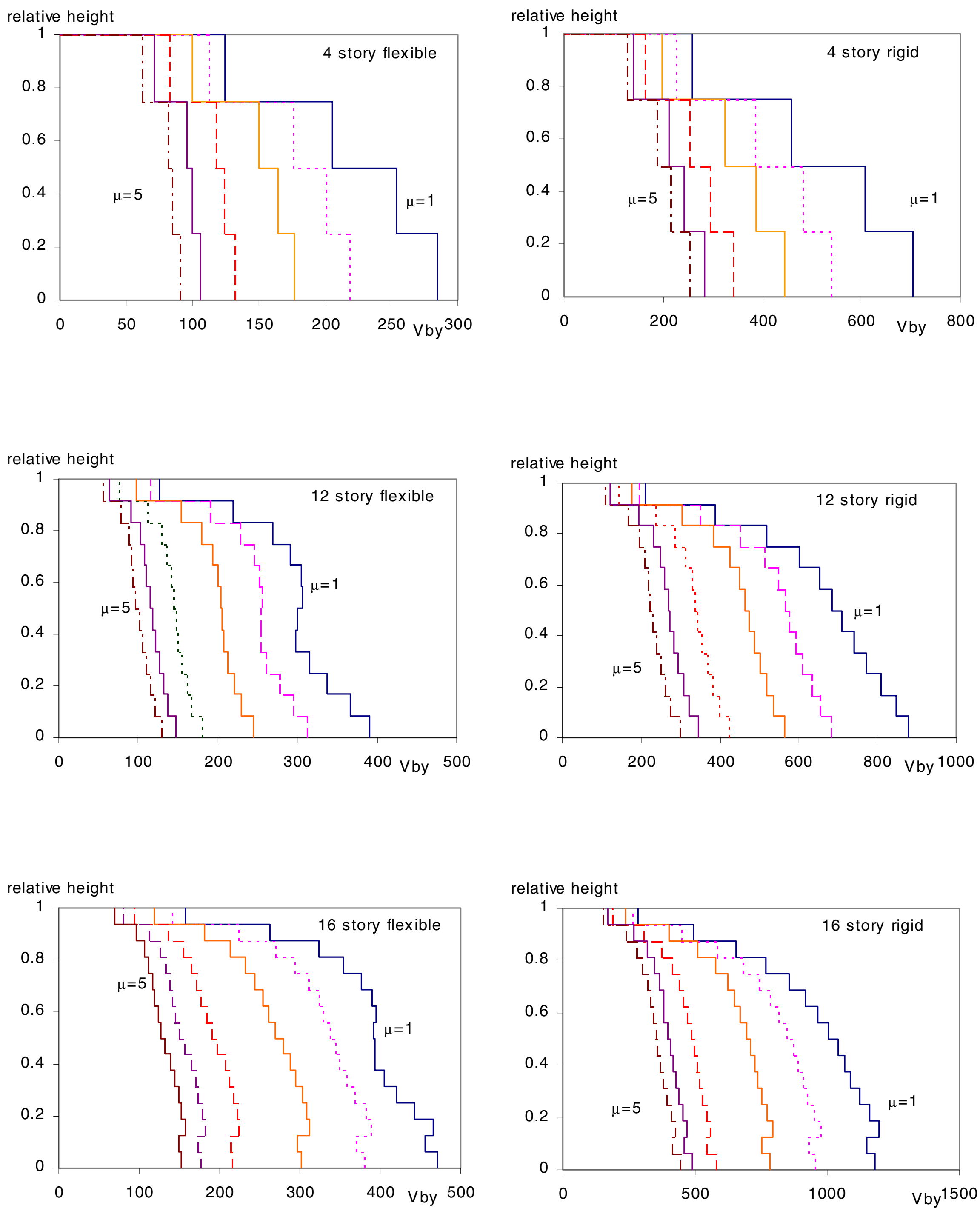
Method of Analysis.
Dynamic base shear and the lateral shear distribution over the height was evaluated for six target ductility ratios: 1, 1.5, 2, 3, 4 and 5. It was evaluated using the following methodology:

1. $V_{base}(\mu = \mu_i)$ or base shear required to avoid story displacement ductility demand larger than the maximum allowable ductility ratio μ_i . This base shear was computed by scaling the intensity of the ground motion until the maximum story displacement ductility ratio in the MDOF structure was, within a 1% tolerance error, equal to the target ductility. The scaling factor was obtained using an iterative procedure using Drain 2DX [2].
2. $V_n(\mu = \mu_i)$ when the base shear was obtained , the maximum shear for each story was selected.
3. For the direct comparison of shear distribution with design shears, the design story shears are those obtained from a base shear equal to the strength demand of the corresponding SDOF system and the 1994 UBC seismic load patterns.

RESULTS

The mean dynamic lateral shear distribution for the 4, 12 and 20 level buildings and five different ductility ratios are presented in Figure 3. The following can be noted from this figure:

1. The dynamic story shears for both four levels buildings (flexible and rigid) are quite similar, having a similar first mode distribution for the elastic behavior.



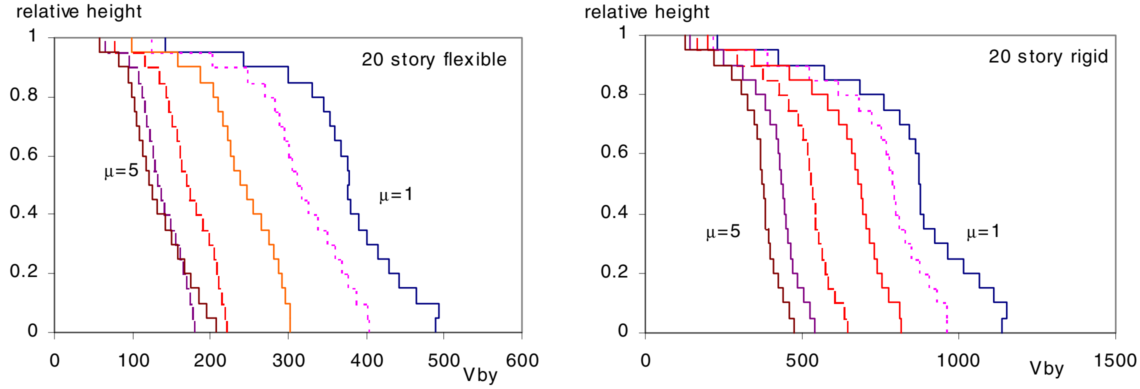


Figure 3. Mean dynamic lateral shear distribution, for ratio ductilities of 1, 1.5, 2, 3, 4 and 5.

2. The shear distribution for the 12 story buildings is different for the flexible system than for the rigid system. As the systems turns more flexible, the higher mode contribution appears (explained on next section), changing the shear distribution pattern. For the elastic case the shear distribution turns into a more rectangular distribution on the mid level of the flexible system; this effect changes as the level of ductility increases.

3. For high buildings as the 20 story flexible and rigid systems, the elastic shear distribution presents a similar pattern: a higher shear on the second and third level than the base shear, a constant shear for the mid-level stories and a rough change of shear in the upper levels. This latter pattern is also present for ductilities of 1.5 and 2 (first stages of the inelastic systems), but for high levels of ductilities the shear distribution turns into a more smooth step by step distribution with the highest shear on the base.

Higher mode influence.
While plotting the shear distribution for every building of this study, some ground motions made mid and high level systems to behave as the graphics shown in Figure 4.

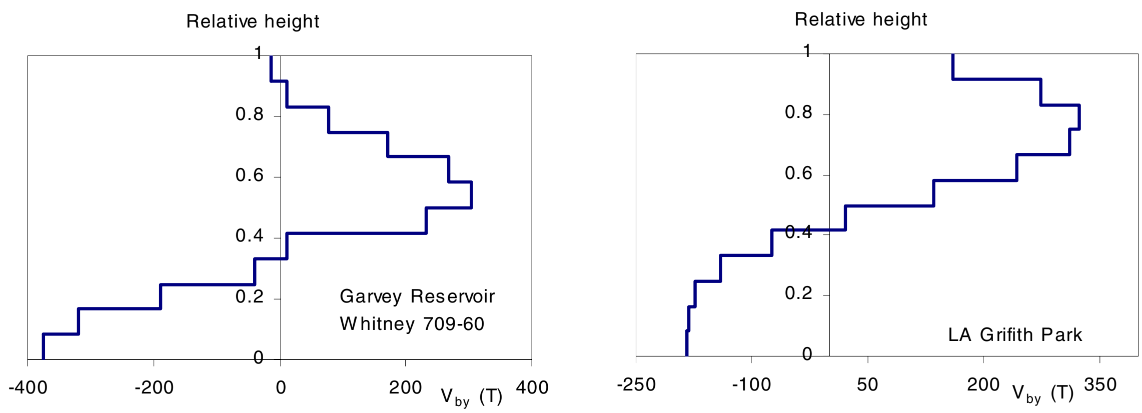


Figure 4. Dynamic elastic lateral shear distribution for the 12 story flexible building.

This elastic shear distribution shows that MDOF systems of 12 stories or more, due to particular ground motions which have in common certain frequency content (Santa-Ana, P. [3]), have a shear distribution with the influence of higher mode effect. In this particular case, the second mode have more influence than other modes. As the systems turns to be more inelastic, this influence diminish, as it was shown in Figure 3, having a higher shear at the base than in other levels.

This higher mode influence do not reflect in the mean shear distribution shown in Figure 3 for the 12 story buildings, because few buildings presented a behavior as the previous; but it is clear than for higher level structures, in particular flexible systems, the influence of the second and third mode higher as shown in Figure 3 for the 16 and 20 story flexible and rigid systems.

Influence of the number of stories and ductility.
In Figure 5 a comparison of the shear distribution of all the buildings studied, in function of the number of stories and for 3 different levels of ductility is presented. Flexible buildings were plotted separate from rigid buildings because each group gather towards a determinated base shear and as a group present a special behavior, indicating that the fundamental period of a MDOF system do not have influence on the shear distribution. The following observations can be made from this figure:

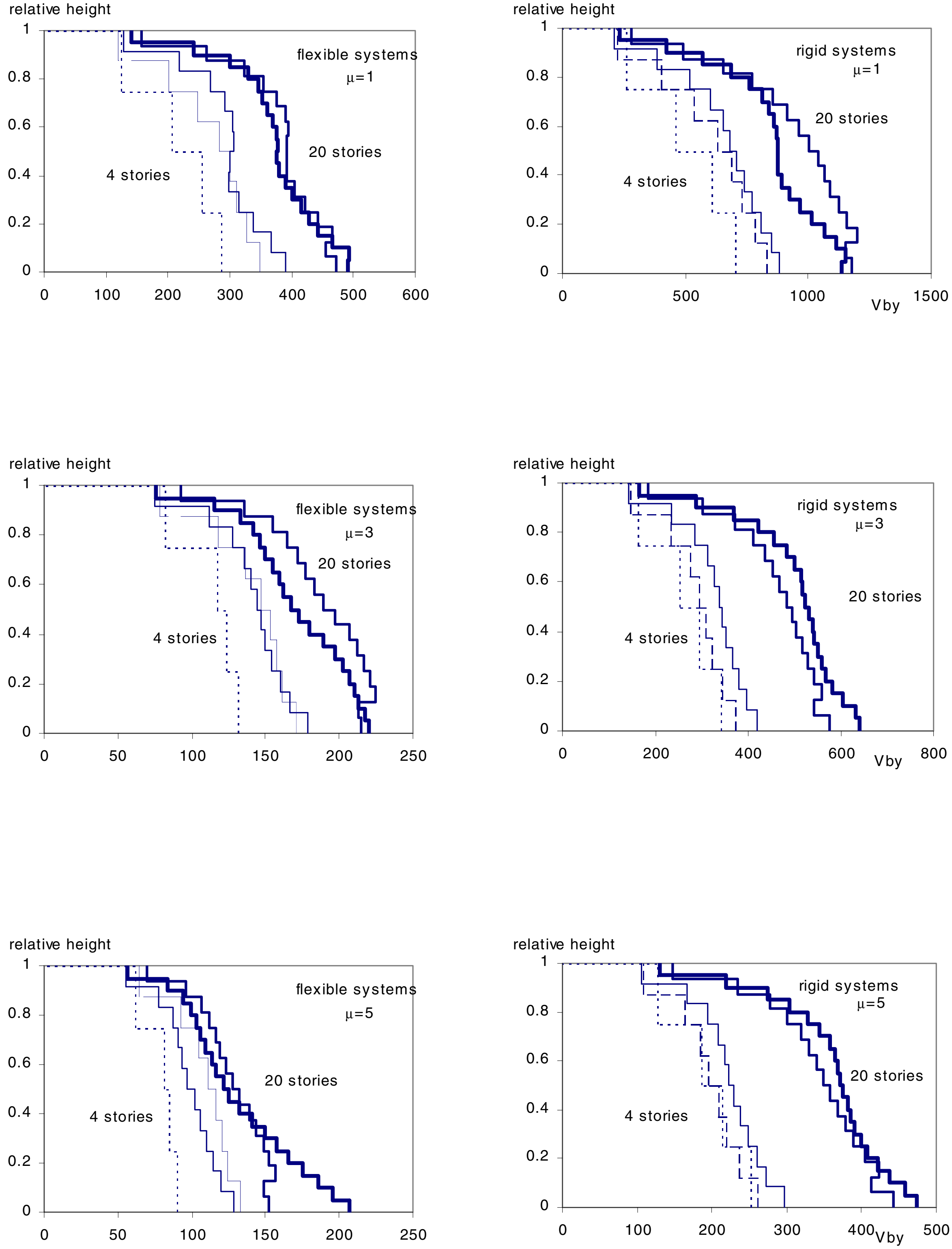


Figure 5. Comparison of shear distribution in function of the number of stories and level of ductility. Thick lines represents higher buildings; dashed lines represents low buildings.

4. For the 16 and 20 story elastic systems, flexible and rigid, the higher shear is located at the second and third story being greater than the base shear. The shear distribution for 16 story rigid system follows a “parabolic” pattern, while the remaining 16 and 20 story elastic systems present a combination of patterns for the shear distribution: a triangular at the base, constant in middle levels and parabolic at higher levels.

5. For the 4 and 8 story (short buildings) elastic systems the shear distribution has an inverted triangular pattern.

6. For considerable levels of ductility, $\mu = 3$, the flexible systems show different behaviors: a) the 16 story flexible building presents a “parabolic” pattern of shear distribution, and the maximum shear is located in the third level; b) the 20 story building shows a pattern similar to an inverted triangular shape; c) for short buildings, the shear distribution seams to be a rectangular shape.

7. For tall rigid structures with moderate and high level of ductility, the shear for the lower stories is higher than for middle stories where the shear is for practical purposes the same in all these levels; again for short structures the shear distribution is a rectangular constant shape.

8. For high levels of ductility the flexible systems have different behaviors: a) for tall structures there is no pattern; b) the 20 story building presents a linear distribution (inverse triangle) while for the 16 story building presents two sections: at the base a rectangular shape and then a linear distribution upward; c) for the 4 story structure the distribution is a rectangular shape.

Comparison of dynamic shear distribution with design story shears.

Figure 6 shows an example of the mean of dynamic shear force distribution, normalized with respect to the design story shears (UBC-94 seismic load pattern) for all buildings plotted in separate graphs flexible and rigid systems. The following can be noted from this figure:

9. For elastic flexible systems the dynamic story shears are higher in upper stories (0.7 of relative height) than those assumed by the code distribution. This behavior is present in all buildings, increasing as the number of stories increase. For the lower stories dynamic story shears are lower than the distribution assumed by the code, implying that code overestimate the shear distribution in lower levels and underestimate shears in upper stories.

10. For low levels of ductility, $\mu = 3$, flexible systems attracted more dynamic shear than the assumed by the code with this same level of inelastic behavior. For short height buildings the dynamic shear distribution is higher in all levels than the distribution assumed by the code. For mid and tall building the dynamic story shears are higher in upper stories (0.4, 0.5 and 0.6 for 12, 16 and 20 story respective) and lower for lower stories than those assumed by the code. The level of the shear underestimated increases from 2 to 3.2 times the design shear.

11. For high levels of ductility, $\mu = 5$, all structures have a dynamic story shear higher than that assumed by the code for this ductility level. This behavior in particular shows that when a building is designed according to the shear distribution proposed by the code for this level of ductility, the structure will be able to developed higher demands of ductility than expected. The maximum difference of dynamic and design shears is present in upper stories, showing that the dynamic shear is 4 times higher than the shear assumed by the code.

12. Also for high level of ductility, dynamic base shear is higher than the design base shear for all buildings.

13. For the rigid systems considered in this study, all structures present higher shears than those assumed by the UBC code, but the pattern of behavior is similar to that of flexible systems.

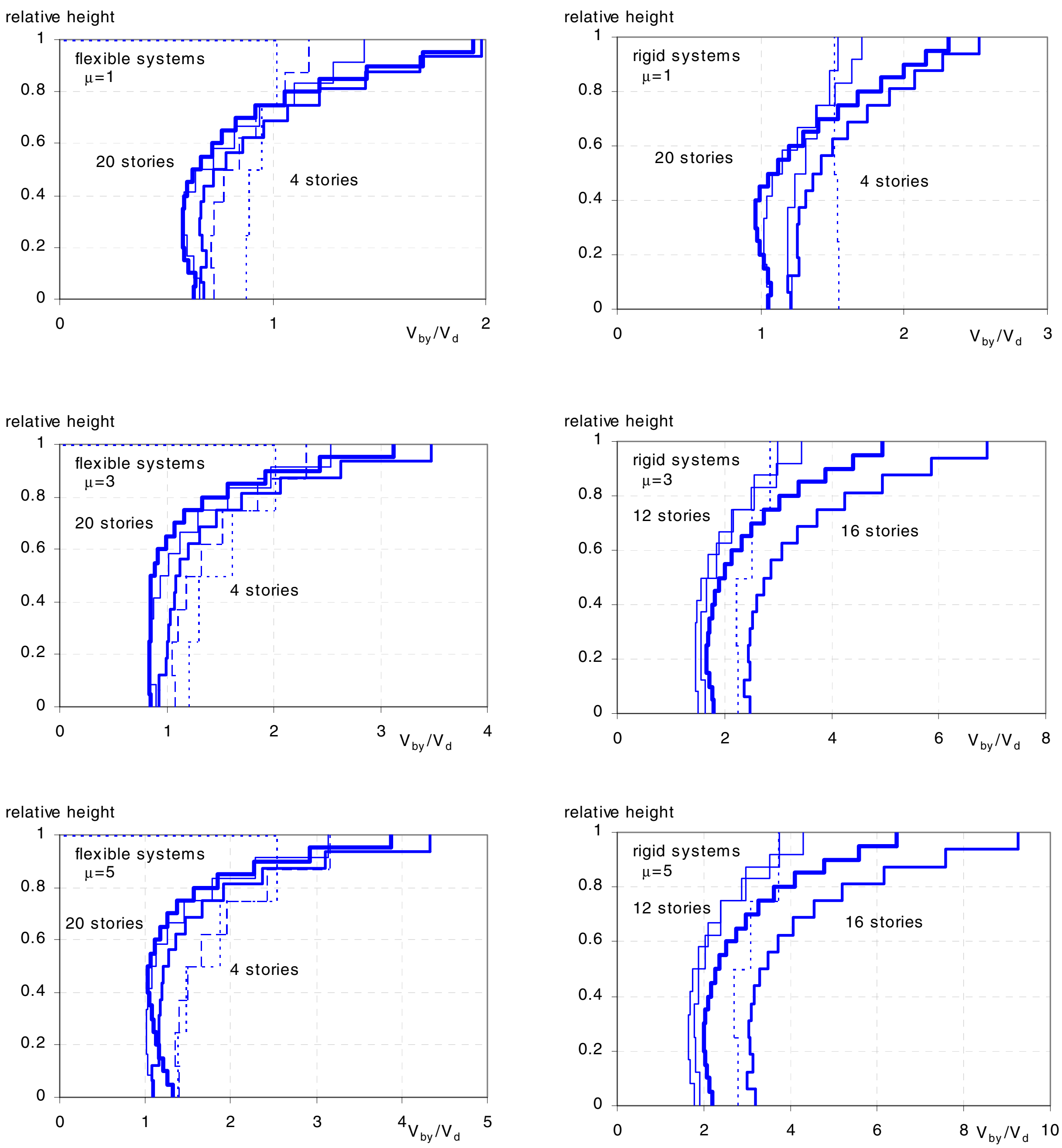


Figure 6. Comparison of dynamic shear distribution to the code shear distribution (UBC-94) in function of the number of stories and level of ductility.

CONCLUSIONS

The aim of this study was to investigate the behavior of the shear distribution over the height of a building. The influence of important parameters as the level of ductility, number of stories and flexibility of the systems were studied. The following conclusions were obtained:

14. The shear distribution for low level structures follows an inverted triangular shape. For this low level structures, as the level of inelasticity increases this pattern of shear distribution changes from an inverted triangle to a rectangle.
15. As the number of levels on a building increases, the shear distribution pattern changes to a parabolic pattern or a combination of linear, rectangle and parabolic pattern for the bottom, mid and higher stories of the systems.
16. For higher level structures, in particular flexible systems, the influence of the second and third mode is higher, reflecting this influence on the mean shear distribution for elastic and low inelastic behavior.
17. The fundamental period has no influence on the shear distribution.
18. When comparing dynamic shears with design shears: a) for elastic flexible systems the dynamic story shears are higher in upper stories than those assumed by the code distribution; b) for the lower stories dynamic story shears are lower than the distribution assumed by the code. c) for high levels of ductility all structures have a dynamic story shear higher than that assumed by the code for this ductility level; d) for rigid systems as the considered in this study, present higher shears in all cases (elastic and inelastic) than those assumed by the UBC code [4], but the pattern of behavior is similar to that of flexible systems.

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