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Shear wall effect on material consumption based on seismic design

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Preliminary note

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Shear wall effect on material consumption based on seismic design

The question of material consumption is one of the most important issues in seismic design of multi-story frames. The paper illustrates how material consumption can be reduced by utilizing shear wall according to the Performance-Based Seismic Design (PBSD). For this purpose, different story frames with and without shear walls are designed In addition, a simple algorithm is proposed for monitoring global response of the system. The results explicitly show that the material consumption in Dual System is lower when compared to the Frame System.

Key words:
moment resisting frames, dual system, life safety, target displacement, PBSD

Prethodno priopćenje

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Utjecaj posmičnih zidova na utrošak materijala na temelju seizmičke analize

Utrošak materijala jedan je od najvažnijih ciljeva pri seizmičkom projektiranju višekatnih okvira. U članku se predlaže smanjenje utroška materijala uporabom posmičnih zidova na temelju seizmičke analize konstrukcije prema njezinim svojstvima (Performance-Based Seismic Design - PBSD). U tu su svrhu analizirani višekatni okvirni sustavi sa i bez posmičnih zidova. Uspoređivan je dobiveni pomak s ciljanim pomakom te je predložen jednostavan algoritam za praćenje općeg odziva sustava. Rezultati jasno pokazuju da je utrošak materijala u dvojnom sustavu manji nego u okvirnom sustavu.

Ključne riječi:
okvirni sustav, dvojni sustav, ciljni pomak, PBSD

Vorherige Mitteilung

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Einfluss von Scherwänden auf den Materialverbrauch beim seismischen Bemessungsverfahren

Beim erdbebengerechten Entwurf von mehrstöckigen Rahmenkonstruktionen spielt der Materialverbrauch eine bedeutende Rolle. Die vorliegende Arbeit analysiert die mögliche Reduzierung des Materialverbrauches durch die Nutzung von Scherwänden beim verhaltensorientierten seismischen Bemessungsverfahren (engl. Performance-Based Seismic Design - PBSD). Daher sind verschiedene mehrstöckige Rahmensysteme mit und ohne Scherwände. Ein einfacher Algorithmus für die Ermittlung des globalen Strukturverhaltens ist vorgeschlagen. Den Resultaten zufolge ist der Materialverbrauch für Dualsysteme bedeutend geringer im Vergleich zu Rahmensystemen.

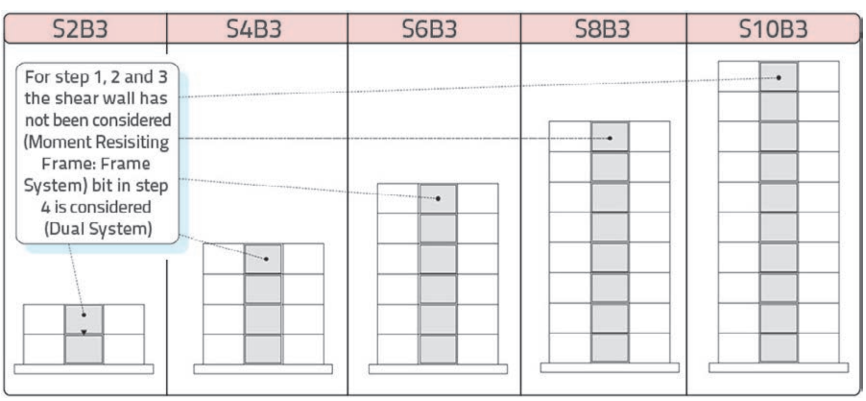
Schlüsselwörter:
Rahmensystem, Dualsystem, Verschiebung im Grenzzustand der Tragfähigkeit, PBSD

1. Introduction

Traditionally, two requirements must be satisfied to design a structural system with respect to lateral forces: sufficient sectional resistance, and sufficient resistance to lateral displacement. On the other hand, most of the time, in civil engineering the problem behaves in linear elastic fashion under service loads. In structures, before the ultimate state and failure is reached, a great deal of nonlinearity is exhibited due to either material nonlinearity and/or geometric nonlinearity, which can lead to the change of stiffness, strength, ductility, and natural frequency. This study aims to introduce the nonlinear approach to evaluate the efficiency of Frame Systems (Moment Resisting Frames) by conducting the Performance-Based Seismic Design (PBSD) so as to meet the abovementioned basic requirements.

In the field of construction, owners are usually not eager to utilize shear wall due to economic issues, i.e., considerable material consumption, and hence they tend to transfer the risk to design professionals. This negligence is studied to show the influence of construction decisions on economic issues and life safety effectiveness. Therefore, the percentage of material savings by using shear wall with regard to the Life Safety (LS) damage control is studied as a means to achieve the most optimum performance and an economical frame system. To obtain this percentage, five RC frames (Figure 1) have been considered and analysed by ETABS2000 (analysis and design software). All structures (2D frames) are subjected to earthquake load estimated according to EN 1998-1 [1] as seismic demand, and it is assumed that all structures are located in an earthquake-prone zone (a = 0.35 g).

The number of storeys is assumed to be two (2S), four (4S), six (6S), eight (8S) and ten (10S) in the three-bay frame (3B) for each model. The height of each storey is 3.2 m, and the length of each bay is 4 m in all frames. The distributed dead and live loads are considered to be 20 and 10 N/mm, and are applied to the beams at all stories. In Tables and Figures, "S" denotes the number of stories, and "B" denotes the number of bays. Material specifications are as fallowing;



* Frame system is considered in the first analysis, and the combined one is considered in the second analysis (frame and vertical reinforced-concrete wall)

Figure 1. Geometry and names of studied frames

f_c = 25 N/mm^2 (B - 300), f_y = 400 N/mm^2 (A - III), f_{ys} = 300 N/mm^2 (A - II), Consequently the strong column and weak beam rule is needed to meet seismic requirements. The Nonlinear Static Pushover Analysis (NSPA) is used and, among different levels of performance, the Life Safety (LS) level has been adopted as the basic damage control level. The frame pushing continues until the signs of the LS plastic hinge occur (target capacity).

Today, the amount of structural damage has been well documented, with respect to PBSD, by many researchers (Habibi and Izadpanah [2], Arjomandi et al [3], Rofooei and Imani [4]), and a number of studies have been presented on the effects various structural configurations have on the performance of multistorey buildings (Naresh Kumar et al [5], Habibi and Izadpana [2]).

Inel and Baytan Ozmen [6] discuss user-defined nonlinear hinge properties and default-hinge properties, available in some programs based on the ATC-40 guidelines [7] and FEMA-356 [8]. Some other papers show seismic performance of existing building with regard to different versions of specific codes, and according to different codes (Rama Raju et al [9], Malekpour et al [10]).

It should also be noted that one paper has introduced optimization in the selection of structural systems for seismic design of reinforced concrete high-rise buildings. Here, the authors present the effect of selecting various structural systems on economic performance of the project, without using the Target Displacement Analysis (Katkhoda and Knaa [11]).

Although all of the cited papers show successful application of PBSD for multistorey buildings, they do not discuss the percentage of material savings (steel bars and concrete) that can be made by using shear wall with regard to the Life Safety (LS) damage control level, for the purpose of achieving the most stable and economic RC frame system.

2. Characterization of the Problem

Generally, many different regions of world are hit every year by several destructive earthquakes, which causes an extensive loss of life and property damage. On the other hand, reinforced concrete (RC) frames are designed to resist seismic load and control lateral displacement, which is related to the behaviour of structures. For this purpose, RC frames assume vertical loads and control lateral displacement (story drift). In this respect, the systems subjected to load are divided into:

a) moment resisting RC frame (bare frame),
b) frame with shear wall (dual system).

This study proposes the Performance Based Seismic Design (PBSD) by which all designers can achieve both displacement control and proper behaviour of structures during seismic action. As this paper shows, dual system can improve the Performance Point Displacement (D_{PP}) and Life Safety Displacement (D_{LS})of structures.

3. Performance Based Seismic Design (PBSD)

Traditionally, the earthquake load (seismic demand) has been reduced for linear design by dividing the base shear by a reduction factor (R), which leads to elastic design. This approach shows that the earthquake load is proportional to the building mass (5-10 % of building weight). But, according to the ATC 40, a multilinear idealized load-deformation curve (simplified backbone nonlinear hysteresis curve, Figure 2) is defined to assign structural components for the conduct of the NSPA. The NSPA is used to provide for a natural behaviour of structures. For this purpose, the capacity-spectrum method has been used.

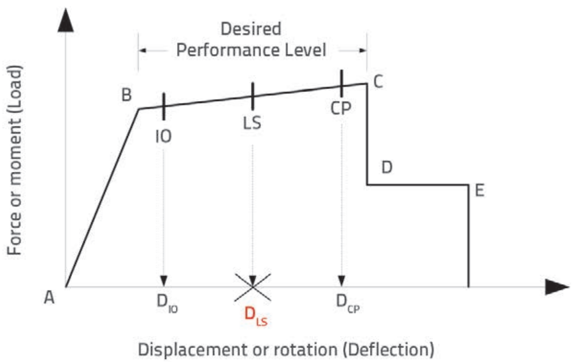


Figure 2. Force–deformation relationship of a typical plastic hinge

The capacity-spectrum method is a nonlinear static procedure in which a capacity curve is developed for a building. The capacity curve is a plot of base shear at various lateral-load increments, versus lateral displacement of building at the roof level. The capacity curve typically consists of a series of straight line segments with decreasing slope. The decreasing slope shows the progressive degradation in structural stiffness that occurs when the building is subjected to an increased lateral displacement, yield, and damage. Before the first plastic hinges, the behaviour of the structure is linearly elastic. After the yield of the structure, the increasing lateral load causes development of more plastic hinges in the structure. This process continues until a mechanism is formed in the structure, at which point it reaches the structural stability level.

The Capacity spectrum curve for the structure is obtained by transforming the capacity curve from lateral force (base shear) versus lateral displacement (roof displacement) coordinates, to spectral acceleration (S_a) versus spectral displacement (S_d) coordinates, and this by using the modal shape vectors, participation factors, and modal masses obtained from the modal analysis of the structure. In the next step, the design spectrum is transferred from spectral acceleration versus period coordinates to spectral acceleration versus spectral displacement. The design spectrum is plotted in the format known as the Acceleration-Displacement Response Spectra (ADRS).

In the final stage, the capacity and demand curve can be drawn in the same plot because both of them are in the same coordinate system. The intersection point between the capacity and demand curve is called the performance point. Once the LS level sign (between the points B and C in Figure 2) appears in any member, the incremental load should be stopped, and the roof displacement of the structure showsD_{LS}. The Life Safety (LS) level has been taken into account as the basic performance level (damage control). On the other hand, D_{PP} or Target Displacement in ADRS format has been created by the CSM (Capacity Spectrum Method). Most notably, this is the first study to our knowledge that investigates a specific clear equation in PBSD (Equation 1). If D_{LS} satisfies the following formula, the building is in safe mood in terms of the Life Safety damage control (desirable Performance Level).

$$D_{PP} < D_{LS} < \alpha \cdot D_{PP} \tag{1}$$

The coefficient α is an additional and conservative capacity that has been developed by authors via half of capacity between D_{LS} and D_{CP} from Figure 2. Although, according to the Life Safety plasticisation mechanism, any stages that appear are not accepted in terms of Life Safety control, and are not included in the Life Safety limitation, a conservative consideration should be taken into account. When Life Safety damage signs appear (turquoise colour in ETABS2000), the analyst can still use residual capacity before the Collapse Prevention stage. Based on the ATC 40 default hinge property, authors suggest half of this range (from D_{LS} to D_{CP}) by using the following calculation (normalised formulation). D_{IO} and D_{CP} are instants for the Immediate Occupancy Displacement, and the Collapse Prevention Displacement, which equal to 2 and 6, respectively (D_{LS} = 4). Numbers 2, 4, and 6 refer to those average portions of the deformation that occur after the yield, i.e. to plastic deformation [9].

$$\alpha = 1 + 0,5\,[(D_{LS} - D_{IO})/\,(D_{CP} - D_{IO})] = 1 + 0,5[(4 - 2)/\,(6 - 2)] = 1,25$$

which is substituted in Equation (1) to obtain Equation (2):

$$D_{PP} < D_{LS} < 1,25 \cdot D_{PP} \tag{2}$$

Equation (2) can conveniently be derived as follows:

$$1 < D_{LS} \,/\, D_{PP} < 1,25 \tag{3}$$

4. Methodology approach

The current study involves modelling and analysis of five frames by different story level to measure the effect of the use of shear walls on material consumption. All cases are located in an earthquake-prone zone (a = 0.35) for the purposes of interpreting the effect of ground motion on the behavior of structures. The PBSD is also used in order to find the target capacity and target displacement. The frame pushing continued until the LS plastic hinge signs appeared (target capacity). In this paper, different systems (dual system) are used, so as to change and improve both the D_{LS} and D_{PP} values for structures. As the method shows, if $D_{PP} < D_{LS} < 1{,}25 \cdot D_{PP}$, the structure is capable of carrying lateral load in the specific seismic zone without any Collapse Prevention damage. The following steps are presented to reach the study purpose as an operational algorithm.

First Step: Design the frame without drift control and record final sections for every beam and column element.

Second Step: Define plastic hinge properties for each member (default hinge properties - not user defined hinge properties - for beams - development of plasticisation moment, and for columns - plasticisation through interaction between the bending moment and normal force) in accordance with their behaviour, and conduct Pushover Analysis and see the Displacement at Performance Point, i.e. Target Displacement (D_{PP}) and Displacement at Life Safety LS (D_{LS}) , for mutual comparison (Figure 3).

Not to mention the fact that in the Finite Element Analysis Method, the creation and modification of the finite element mesh is usually the most time consuming task. The ETABS has the capability of using an auto line constraint. The ETABS auto line constraint feature allows user to specify that elements framing into the edge of a shell element be connected to the shell element. Finite element mesh (Improved Bilinear Quadrilateral among other methods) is not explicitly created by the user but is automatically created by assigning meshing parameters to the area objects, such as the mesh size, mesh spacing, and mesh grading. With this capability, the effects of mesh refinement can be studied by defining just a small number of control parameters.

Third Step: Increase the size of the Columns and Beams section, until the D_{LS} passes from the D_{PP} and satisfy the Equation (2).

Forth Step: While the shear wall adds with constant thickness 15 cm to the frames, try to replace the section of beams and columns by the new section with smaller size until the D_{LS} gets bigger than the D_{PP} and satisfy the Equation (2).

5. Results

The effect of Moment Resisting Frames and Dual System on D_{PP} and D_{LS} and, consequently, the amount of material consumption, are shown in Table 3. According to Figure 4, after designing the frame (step one), the designed member sections (beam and column sections) are obtained.

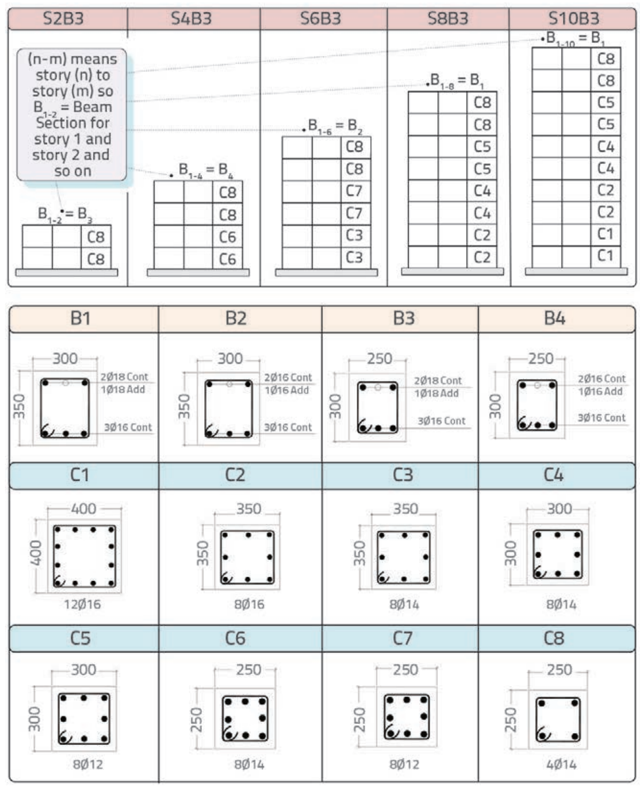


Figure 4. Section properties for all frames in step 1: a) location of each section through the frames; b) section properties for beams and columns (B - beam; C - column)

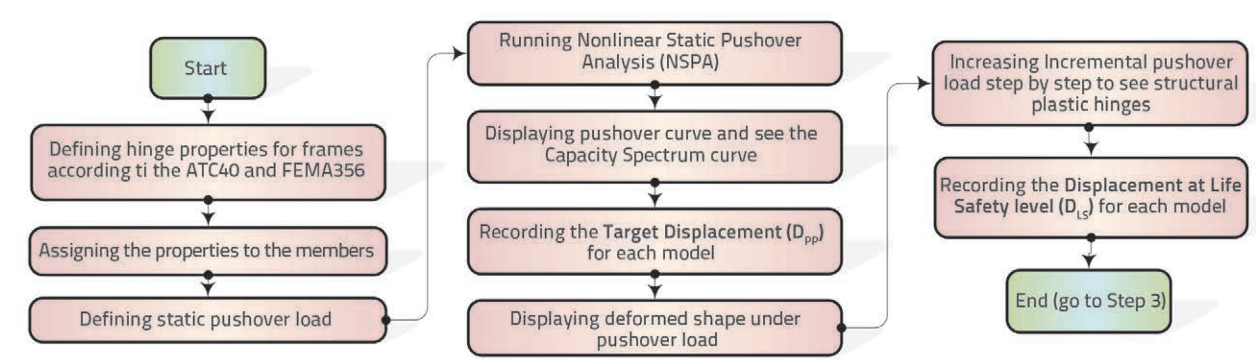


Figure 3. Step 2; PBSD procedure to reach the D_{PP} and D_{LS}

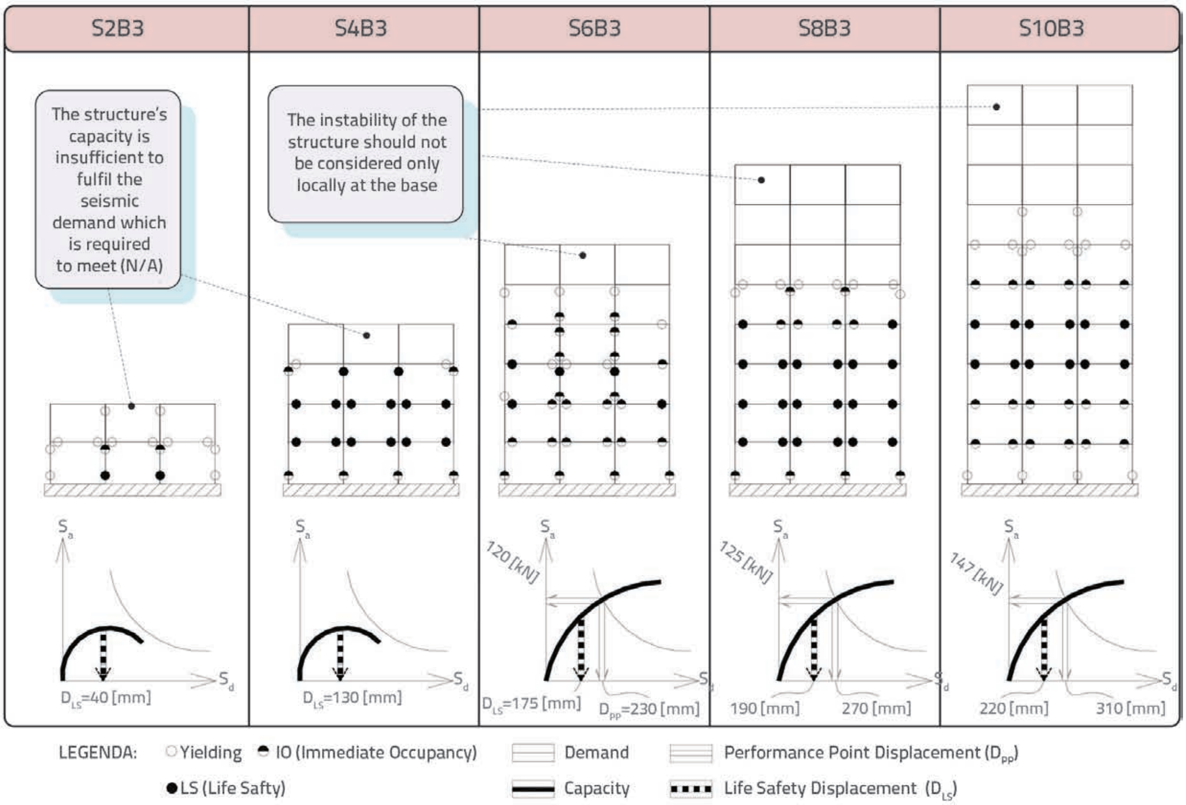


Figure 5. Column and beam section properties, Plastic hinge mechanism with default-hinge properties and their schematic Capacity Curves in Step 2

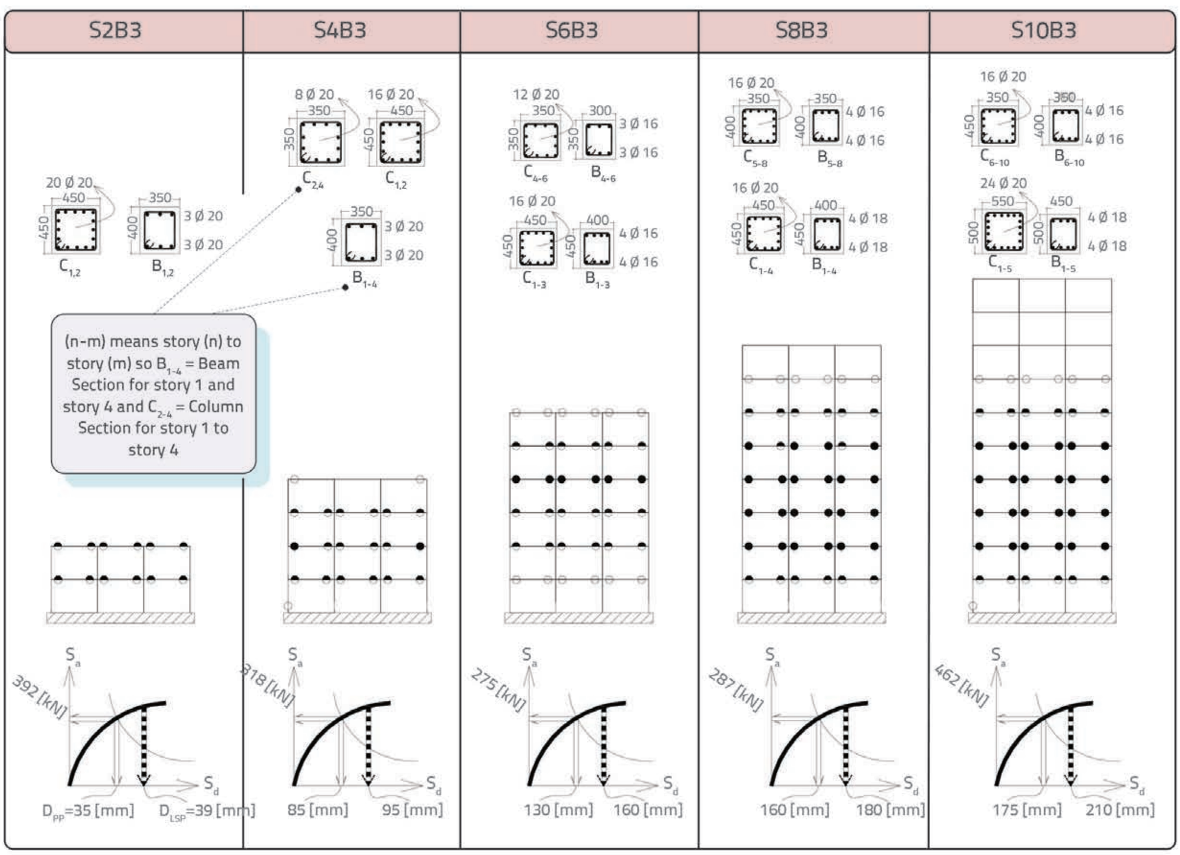


Figure 6. Column and beam section properties, Plastic Hinge mechanism with default-hinge properties and their schematic Capacity Curves in Step 3

Table 1. Number of plastic hinges (PH) at the specific performance levels (Y, IO, LS)

Frames	Step 2 (number of plastic hinges - PH)						Step 3 (number of plastic hinges - PH)						Step 4 (number of plastic hinges - PH)					
	Columns			Beams			Columns			Beams			Columns			Beams		
	Y	IO	LS	Y	IO	LS	Y	IO	LS	Y	IO	LS	Y	IO	LS	Y	IO	LS
S2B3	8	2	2	6	0	0	0	0	0	0	12	0	0	0	0	4	4	0
S4B3	0	6	2	2	0	12	1	0	0	2	16	2	0	0	0	4	11	1
S6B3	4	12	2	4	12	3	0	0	0	12	18	6	0	0	0	4	4	16
S8B3	2	6	0	6	4	20	0	0	0	6	14	22	0	0	0	5	23	4
S10B3	8	0	0	6	18	12	1	0	0	6	12	24	0	0	0	4	22	13

PH - Plastic Hinge, Y - Yielding, IO - Immediate Occupancy, LS - Life safety

At the second stage, in order to satisfy the Step 2, the default plastic hinges have been assigned to the members, and frames responses have been checked. Figure 5 with symbols and legend shows entire figures and location of plastic hinges in the members in terms of different performance level. In this Figure, CSM diagrams (intersection of capacity spectrum - converted pushover curve-and demand curve) are illustrated schematically to show sufficiency of Life Safety Performance of frames.

Although Figure 5 shows that in step 2 the plastic hinges developed in all frame systems (structure's behaviour is ductile), capacities of S2B3 and S4B3 are insufficient to fulfil the seismic demand as required via N/A massage of software (ETABS2000), which is why D_{PP} results have been eliminated. However, as the diagram shows that the D_{LS} for S2B3 and S4B3 are 0.04 and 0.13, respectively. D_{PP} and D_{LS} for S6B3, S8B3 and S10B3 are 160, 220, 200 and 230, 300, 310 millimetres, respectively. All results

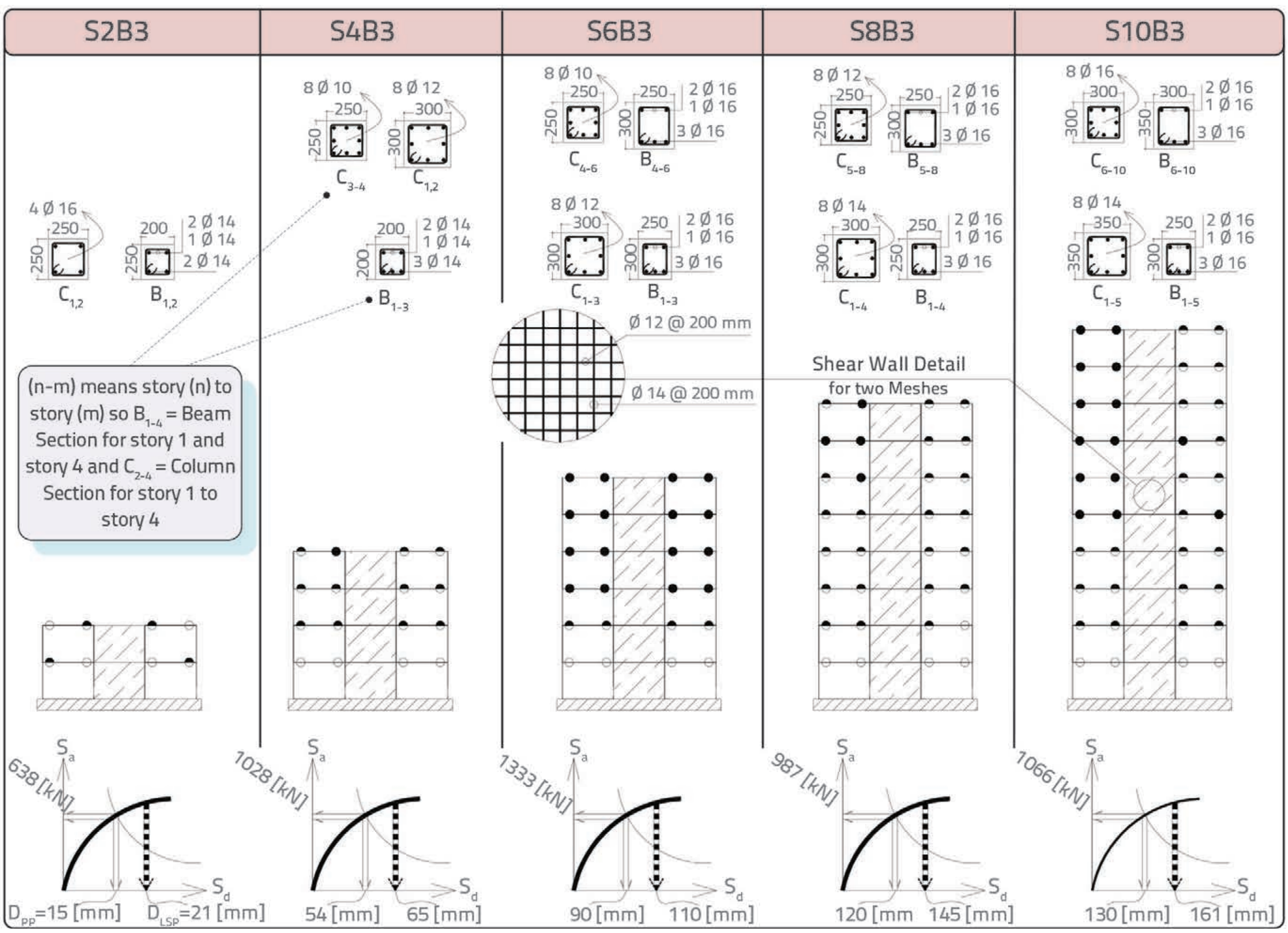


Figure 7. Column and beam section properties, plastic hinge mechanism with default hinge properties and their schematic Capacity Curves in Step 4

are shown in Table 2. As shown in Figure 6, in the third step, plastic hinges have developed in all frames systems and most plastic hinges have been generated through beams (then the strong column and weak beam requirement is satisfied). All results are presented in Table 2.

According to Step 4 of the methodology, shear walls must be added to the frames and section properties of members are simultaneously changed until the D_{LS} passes from D_{PP} . Figure 7 shows that all frames are able to withstand the demand earthquake (Eq. 2) by selecting the specific member sections at the top part of the Figure. All results are given in Table 2.

In the process of creating the pushover curve, a different range of plastic hinges (PH) has been generated, with differing quality and quantity parameters. There is a relationship

Table 2. Summary of displacement results for demand and Life Safety

Frames	Step 2			Step 3			Step 4		
	D_{PP}	D_{LS}	$1{,}25 \cdot D_{PP}$	D_{PP}	D_{LS}	$1{,}25 \cdot D_{PP}$	D_{PP}	D_{LS}	$1{,}25 \cdot D_{PP}$
S2B3	N/A	40	N/A	35	39	44	15	21	19
S4B3	N/A	130	N/A	85	95	106	54	65	68
S6B3	230	175	288	130	160	163	90	110	113
S8B3	270	190	338	160	180	200	120	145	150
S10B3	310	220	388	175	210	219	130	161	163

Table 3a. Summary of reinforcement and concrete consumptions for each step - Summary of Consumptions for Steps 1 and 2

Frames	Step 1 and 2					
	Steel bars usage [kg]			Concrete usage [kg]		
	Column	Beam	Total weight	Column	Beam	Total weight
S2B3	124	230	354	3.840	4.320	8.160
S4B3	372	422	794	7.680	8.640	16.320
S6B3	552	625	1.177	15.206	15.552	30.758
S8B3	878	935	1.813	28.032	18.144	46.176
S10B3	1.364	1.169	2.532	37.862	22.680	60.542

Table 3b. Summary of reinforcement and concrete consumptions for each step - Summary of Consumptions for Step 3

Frames	Step 3					
	Steel bars usage [kg]			Concrete usage [kg]		
	Column	Beam	Total weight	Column	Beam	Total weight
S2B3	1.263	355	1.618	12.442	8.064	20.506
S4B3	1.516	711	2.226	19.968	16.128	36.096
S6B3	2.653	796	3.449	29.952	24.624	54.576
S8B3	4.042	1.373	5.415	44.544	36.864	81.408
S10B3	6.315	1.716	8.031	77.568	48.960	126.528

Table 3c. Summary of reinforcement and concrete consumptions for each step - Summary of Consumptions for Step 4

Frames	Step 4							
	Steel bars usage [kg]				Concrete usage [kg]			
	Column	Beam	Shear wall	Total weight	Column	Beam	Shear wall	Total weight
S2B3	162	144	568	874	3.840	2.880	9.216	15.936
S4B3	308	346	1.136	1.790	9.370	4.608	18.432	32.410
S6B3	463	682	1.704	2.849	14.054	12.960	27.648	54.662
S8B3	859	910	2.272	4.041	18.740	15.840	36.864	71.444
S10B3	1.428	1.137	2.840	5.405	32.640	25.920	46.080	104.640

between the number of PH and structural behaviour. When the numbers of PH at the specific performance level (i.e. Life Safety) increase and develop throughout the system, it means that the building globally behaves at that particular level. For this purpose, PH numbers are summarized in Table 1 in terms of their performance levels. As shown in Table 2, in Step 2 D_{LS} is lower than D_{PP} while in Steps 3 and 4, D_{LS} is greater than D_{PP} and the amounts of $1.25 \cdot D_{PP}$ are presented in the last column of each step.

6. Discussion of results

As can be seen in Table 2, D_{PP} is greater than D_{LS} in Step 2. It means that the frame capacity is insufficient to fulfil the seismic zone requirement (demand). in Steps 3 and 4, D_{PP} is lower than D_{LS} . In addition, If $D_{LS} < 1{,}25 \cdot D_{PP}$, the structure can carry lateral load in the specified seismic zone (a = 0.35) without any Collapse Prevention damage (Equation 2).

As can be seen in Figure 6, in the third step, all frames of adequate sections are able to withstand the demand earthquake (Equation 2), and most plastic hinges are generated through beams (then the strong column and weak beam requirement is met). All the results are listed in a single table (Table 2).

Table 2 also shows that the decrease of D_{PP} in Step 4 is highest as compared to D_{PP} in Step 3. This difference is relevant to the presence of shear wall in the last step. Bilinear Quadrilateral among other Finite Element Methods is assigned to shear wall by meshing the desired area. The effects of fine mesh can be studied in the finite element analysis of wall surface by simply adjusting the wall meshing option. However, some limitations should be noted. Although our hypotheses were supported by nonlinearity of the entire system, the shear wall was not assessed due to limited software option. Future work should therefore include the nonlinearity of shear wall in this combined system.

The weight of beams, columns and whole frames is summarized for each step in Table 3 in order to study the effect of life safety damage control on the total weight of concrete and steel materials for each frame. All results given in Table 3 are illustrated in Figure 8 by line chart.

Figure 8.a shows that in Step 4 the consumption of materials is lower than in Step 3, and this especially for frames exceeding 6 storeys in height. Figure 8.b shows the same result for steel bars. It indicates that the use of shear wall is more effective in higher stories.

Based on the summary given in Table 3, the percentage of material consumption (reinforcement and concrete) in step 3 is greater than in step 4 with respect to step 2 (Table 4). According to Table 4, if S2B3 results are ignored, material savings amounting to 12 % for reinforcement and 32 % for concrete are achieved when shear walls are used, instead of an increase in the size of column and beams.

This study has revealed that dual systems (adding shear wall

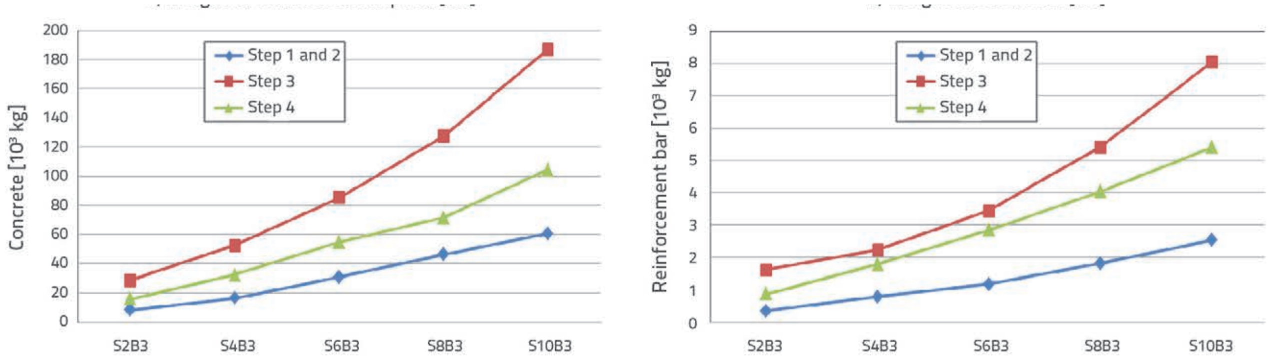


Figure 8. Total weight of material: a) concrete consumption; b) reinforcement bar consumption

Table 4. Comparison of steel rebars and concrete consumption

Frames	Concrete			Steel bars		
	Step 3/Step 2	Step 4/Step 2	Comparison [%]	Step 3/Step 2	Step 4/Step 2	Comparison [%]
S2B3	2,5	2,0	29	4,6	2,5	85
S4B3	2,2	2,0	11	2,8	2,3	24
S6B3	1,8	1,8	0	2,9	2,4	21
S8B3	1,8	1,5	14	3,0	2,2	34
S10B3	2,1	1,7	21	3,2	2,1	49
		Average comparison	**12**		Average comparison	**32**

instead of increasing the size of members) lead to reduction of both D_{LS} and D_{PP} for about 49 % and 67 %, respectively, based on Step 2 results (Table 5), while bare systems (increase in the size of members instead of adding shear wall) just pulls the D_{PP} down by 49 % without any change in D_{LS} .

Table 5. D_{LS} and D_{PP} ratio in Steps 3 and 4 based on Step 2drugim

Frames	Step 3 / Step 2 [%]		Step 4 / Step 2 [%]	
	D_{LS}	D_{PP}	D_{LS}	D_{PP}
S2B3	0	N/A	-33	N/A
S4B3	-25	N/A	-45	N/A
S6B3	0	-48	-48	-74
S8B3	-5	-47	-47	-67
S10B3	5	-52	-52	-61
Average	0	-49	-49	-67

4. Conclusion

Using NSPA and PBSD, the effect of shear wall use on material consumption is presented in terms of structural non-linear behaviour. In this study, a simple formula (Eq. 2) is presented for the first time in order to monitor the damage to structures in terms of each level of performance. The proposed equation is applied to five RC moment frames (by assigning plastic hinge properties at both ends of beams and columns) subjected to incremental vertical load including 2, 4, 6, 8, and 10 storeys by 3 bays. The study shows that an increase in the size of structural members (beam and column) to satisfy the Equation (2) causes significant material consumption. On the contrary, the use of shear wall within the frames (dual system) improves behaviour of the building in terms of PBSD conditions, especially at higher storeys, while also reducing the amount of steel and concrete required during construction.
The dual system causes 12 % and 32 % savings in the consumption of concrete and steel bars, respectively, for the desired performance level (life safety damage control level). D_{LS} and D_{PP} for Dual systems (adding shear wall instead of increasing the size of members) have been reduced by about 49 % and 67 %, respectively. On the other hand, bare systems, in which the size of members is increased instead of adding shear wall, just pull the D_{PP} down by 49 % without any change in D_{LS} This means that not only a decrease in D_{PP} , but also theD_{LS} moderation, is essential for controlling the amount of structural damage.

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