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INVESTIGATING THE SEISMIC BEHAVIOUR OF SPLIT-LEVEL BUILDING STRUCTURES

S. V. Khonsari[1], G.L. England[2] and M. Kiani[3]

ABSTRACT

The history of the building structures damaged during previous earthquakes reveal that one of the causes of these damages was the existence of some sort of irregularity in the structure of these buildings. In this work, the effects of irregularities due to the split in the levels of various parts of some 2D steel structures (Split Level) on their seismic behaviour are studied. The studied frames consist of five-, ten- and fifteen-storey frames, each with 0, 30, 60, 90, 120, and 150 cm split between the storey levels of the two parts (sides) of the building. The modal analysis of these frames showed that a high percentage of their base shear is transferred to the foundation through the upper-level columns and therefore the lower-level columns have little contribution to this process. Moreover, the comparison between the internal forces and the displacements of these frames obtained through the two methods of analysis, *viz* "modal analysis" and "static analysis" using the proposed method for working out the equivalent static loads, show a fair degree of correlation between their results. Thus, within the context of studied frames, it can be concluded that instead of dynamic (modal) analysis, one can carry out a static analysis using the method of distribution for the equivalent static loads developed and proposed in this paper.

Introduction

The history of previous earthquakes demonstrates that irregular buildings are potentially more vulnerable than their regular counterparts. The main reason is the inappropriate distribution of released energy in such buildings that results in stress concentration in structural elements (Naeim 2001). Despite the diversity of the existing irregularities, they can be categorized into two major groups, geometrical (architectural) and non-geometrical (irregularity in the distribution of mass and/or stiffness). Many seismic codes divide architecturally irregular buildings into those with irregular *Plan* and those with irregularity in *Elevation.* One particular type of the latter comprise split-level building structures (Fig. 1). In these buildings every storey is composed of two/several separate levels (SEAOC 1980).

Most of the buildings built in sites where the ground has a fairly steep slope are necessarily of split-level type. Such sites, if of high seismicity, require the buildings to be

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[1] Assistant Professor, Dept. of Civil Engineering, Sharif University of Technology, PO Box 11155-9313, Tehran, Iran.
[2] Professor, Dept. of Civil and Environmental Engineering, Imperial College of Science, Technology and Medicine, London SW7 2BU, UK.
[3] MSc Graduate, Dept. of Civil Engineering, Sharif University of Technology, PO Box 11155-9313, Tehran, Iran.

designed for earthquakes they are likely to experience during their service life. On the other hand, one of the challenges that structural engineers are facing when dealing with split-level buildings is how to work out the equivalent earthquakes forces and their distribution. Lack of existence of a reliable and accurate method for dealing with this problem forces the engineers to resort to dynamic methods of analysis. While nowadays such analyses are more common and more frequently used by engineers, still they possess many complications and subtleties. Therefore, if an equivalent static method of analysis with a fair degree of accuracy, similar to what is used for regular buildings, can be developed, it will be very beneficial to structural engineers. In this work, an attempt has been made to find a simple, yet accurate method to work out the *"Equivalent Static Loads,"* and the *"Distribution of Such Loads"* amongst various levels of the *Split Level Building Structures.* As an initial step in this direction, a series of split level structural frames were designed and analyzed through the proposed method and modal analysis. The results obtained from the two methods are compared and it is shown that despite the very simple and straightforward logic which is behind the developed method, at least within the context of the studied cases, a good correlation exists between them.

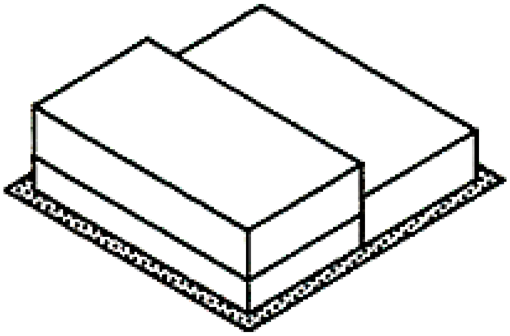


Figure 1. A typical split-level building (SEAOC 1980).

Studied Frames

Frame Characteristics

The studied frames consist of five-, ten- and fifteen-storey frames, each with 0 to 150 cm split between the storey levels with the increment of 30 cm. All of the frames have 6 spans (3 on the lower level foundations, right, and 3 on the higher level ones, left). Using the selected frames, the accuracy of the *"developed static method"* is evaluated. Moreover, the effect of number of storeys on distribution of base shear and the effect of splitting on the behavior of low-level (five-storey) and higher-level (fifteen-storey) buildings is assessed. Fig. 2 shows a typical studied frame.

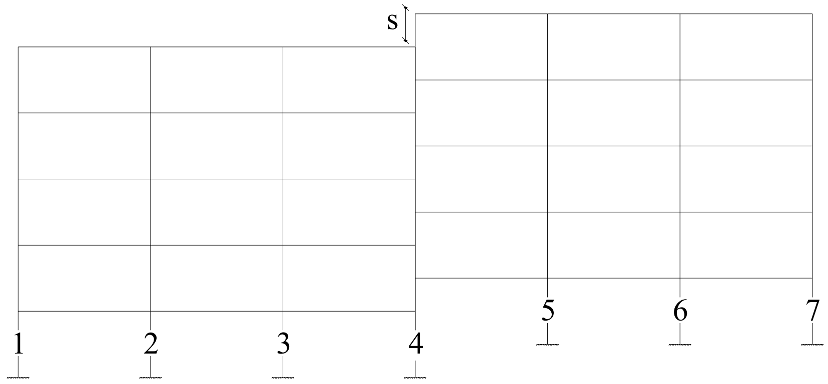


Figure 2. Five-storey frame with "half storey" split (*S*) between floor levels.

Modeling Assumptions

All frames had the same following modeling assumptions:

1. Storey height for all frames was the same and equal to 3 m.
2. Span length and frame spacing (loading width) for all frames were equal to 6 m.
3. All of the supports were fixed.
4. Profiles used for beams and columns were HE-A and HE-B (based on Euronorm 53-62), wide-flange beams and columns, respectively.
5. Designing of frames was based on allowable stress design method of AISC (AISC 1989).
6. Whiplash force of equivalent static load method is applied to the highest level.
7. Damping ratio for all frames was assumed to be 0.05.

Method of Analysis

The selected frames were studied using two different methods of analysis, *static* and *dynamic.* The static analysis was carried out using the Equivalent Static Loads and a very simple proposed method for distributing them on various levels of the structure, based on "*Common Sense.*" However, the dynamic analysis was carried out using Modal Analysis method.

Developed Distribution Method for the Equivalent Static Load

The first stage of using an equivalent static load is finding a Seismic Response Coefficient, which is calculated by various, mostly very similar, methods depending on the seismic code used. The base shear is evaluated from multiplying this coefficient by the total weight of the structure. Now the question that arises is about the distribution of base shear on the building structure. Regarding regular buildings, most of seismic codes distribute the base shear among building levels in proportion to $w_i h_i^k$, in which h_i^k is the first mode shape of the building. Many codes such as UBC (UBC-97 1997), take k equal to 1.

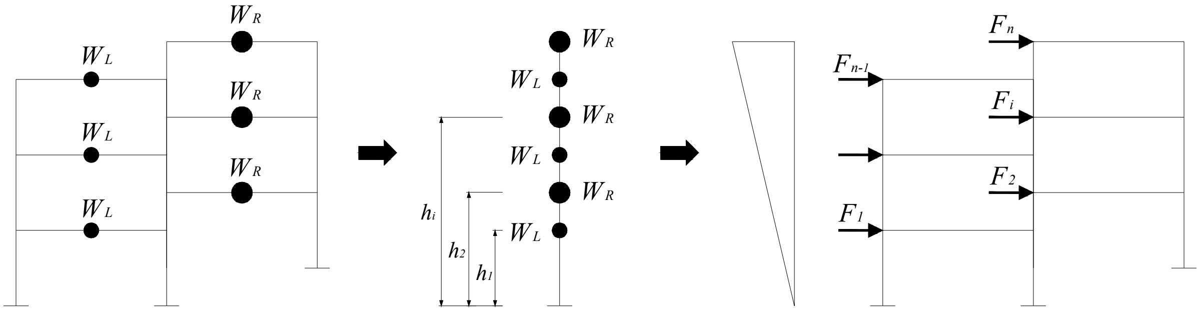
As far as irregular buildings are concerned, the results obtained from such simple and straightforward method of distribution do not correlate with those of their dynamic counterparts. And, split-level buildings are no exceptions in this regard. Dealing with split-level building requires a clear perception about the behaviour of irregular buildings, in general, and about this special type of irregularity, in particular. However, in order to avoid complexities involved in dynamic modeling and analysis of such structures, as well as interpretation of their results, which anyway is not an easy task, some professional engineers resort to various approximate methods to distribute the base shear amongst different levels of the two sides of the building. Some engineers separate the frames from the common column where the levels are split into two parts and use equivalent static method for each separated frame. In other words, in this kind of separating method, the total base shear is divided between the two parts in proportion to their weights and each is divided amongst various levels according to the conventional linear distribution which is normally used in association with the equivalent static load method, $w_i h_i / \Sigma_j w_j h_j$. For instance, if the two parts of the building are identical, total base shear is divided into two equal portions and similar storeys of each part receive the same share from the total base shear of that part. Apparently, there are several flaws in this type of approximation. First of all, the amount of split does not have any role in the share of each level of each part (side) of the base shear—in other words, whether there is a *half story split* between the two parts or a *zero split,* the amount of the lateral force on similar levels is the same. As it is shown later in this paper through dynamic analysis, and, as expected through engineering common sense, this is absolutely wrong. Secondly, the interaction between the two parts, and its role in creating a new balance in the distribution of the total base shear, is totally ignored in this approach. Another approximate approach is to use a regular, un-split frame with each level positioned at the average height of the two similar storeys of the adjacent frames. While this method seems to lead to reasonable results for small amounts of split, as the size of the split increases the results are expected to severely depart from their exact counterparts. Therefore, a need for developing a rational, yet simple, method of distribution for split-level buildings was felt by the authors as a result of which the steps which should be taken to accomplish this task are given below.

First step:
A simple regular structure which may even be a single-column, or a one-bay frame, with the storeys placed at the heights where the storeys of both parts of the main frame are located (i.e. a $2n$-storey frame), is considered.

Second step:
The weight of each level is directly applied to that level. In this step, apparently, if the frame is nonsymmetrical (e.g. when the numbers or the sizes of bays of the two parts are different), calculated weights of the two parts are different. Applied weights are illustrated in Fig. 3 where W_L and W_R are the weights of each storey of left and right parts, respectively.

Third step:
The distribution of static loads is obtained using traditional method of distribution of equivalent static loads on regular buildings, i.e. using the linear distribution proposed by various codes, $w_i h_i / \Sigma_j w_j h_j$.

Fourth step:
In order to complete the procedure, one should just subject every force to its level on the original (split-level) structure.



$$F_i = \frac{w_i h_i}{\sum_j w_j h_j}(V - F_t)$$

Figure 3. Proposed procedure for applying equivalent static load on split-level buildings.

Applying the Whip Force

In the "Modeling Assumptions" section, we assumed that whip force was applied just to the highest level and it was not distributed between the last levels of the two parts. Now we are going to scrutinize the competence of mentioned method of applying whip force by splitting the forces of left and right parts (sides) of the frame.

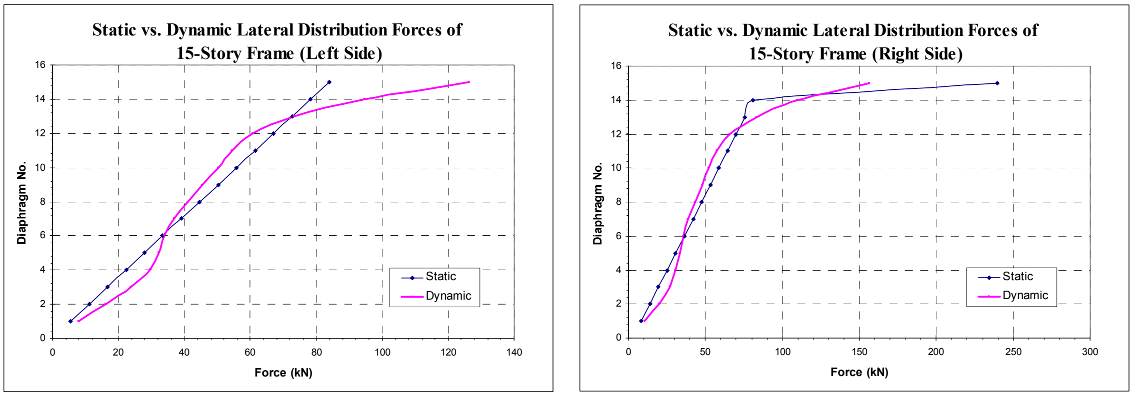


Figure 4. Distributed forces of higher level (right part) and lower level (left part) of the fifteen-storey frame.

As it can be seen in Fig. 4, the magnitude of static whip force in the last level of right side of the frame is much more than its dynamic amount (almost double). On the other hand, dynamic analysis shows that the last level of left side of the frame, which was not subjected to any whip force, needs an additional force. Therefore, in order to complement the proposed method, a modification to the application of whip force should be made. The most simple, yet rational, way to do this is to apply the whip force to the highest levels of both sides of the frame and in proportion to their weights (see Fig. 5 and Eqs. 1 and 2). Using this modification, a much better correlation between the results of the static and dynamic analyses were observed.

$$F_t = (F_t)_L + (F_t)_R \tag{1}$$

$$\frac{(F_t)_L}{(F_t)_R} = \frac{W_L}{W_R} \tag{2}$$

where

F_t : total whip force

$(F_t)_R$: right side whip force

$(F_t)_L$: left side whip force

W_R : weight of right side's last level

W_L : weight of left side's last level

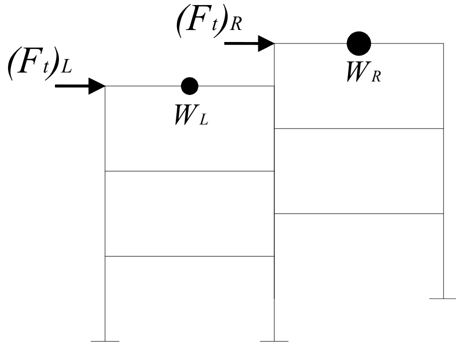


Figure 5. Dividing whip force in proportion to top storeys' weights of the two sides.

Evaluating the Proposed Method's Accuracy

Comparison between Static and Dynamic Base Shears

In order to assess the accuracy of the proposed method of distributing the equivalent static load, the share of the upper foundations of the total base shear (see Fig. 6), R_R (see Eq. 3), worked out by this method and the dynamic method of analysis are compared. The error in R_R is worked out using Eq. 4 and presented in Tables 1, 2 and 3 for 5-, 10- and 15-storey frames with various amounts of split between their two parts.

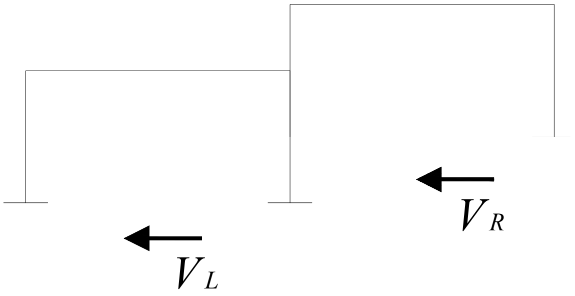


Figure 6. The share of each series of foundations, the higher-level and the lower-level ones, of total base shear.

$$R_R = \frac{V_R}{V} \tag{3}$$

$$Er = \frac{(R_R)_{Dy} - (R_R)_{St}}{(R_R)_{Dy}} \times 100 \tag{4}$$

where
V_R : higher-level foundations shear force
V : total shear force
R_R : ratio of higher-level foundations shear to total shear
E_r : error in percentage
$(R_R)_{Dy}$: higher level foundations shear force obtained from Dynamic analysis
$(R_R)_{St}$: higher level foundations shear force obtained from Static analysis

Table 1. Error percentage for higher-level foundations of five-storey frames.

Split Height of 5-Storey Frame (cm)	**0**	**30**	**60**	**90**	**120**	**150**
$(R_R)_{St}$	0.429	0.481	0.553	0.668	0.707	0.737
$(R_R)_{Dy}$	0.429	0.475	0.542	0.651	0.687	0.714
***Er* (%)**	0.054	1.420	2.037	2.606	2.812	3.151

Table 2. Error percentage for higher-level foundations of ten-storey frames.

Split Height of 10-Storey Frame (cm)	**0**	**30**	**60**	**90**	**120**	**150**
$(R_R)_{St}$	0.421	0.499	0.585	0.687	0.726	0.784
$(R_R)_{Dy}$	0.419	0.492	0.572	0.666	0.699	0.754
***Er* (%)**	0.358	1.423	2.273	3.153	3.863	3.979

Table 3. Error percentage for higher-level foundations of fifteen-storey frames.

Split Height of 15-Storey Frame (cm)	**0**	**30**	**60**	**90**	**120**	**150**
$(R_R)_{St}$	0.413	0.525	0.609	0.694	0.776	0.821
$(R_R)_{Dy}$	0.411	0.518	0.595	0.672	0.746	0.788
***Er* (%)**	0.556	1.504	2.416	3.302	4.021	4.125

As above tables show, the maximum error in the results of the developed method compared with those of modal analysis, for the studied frames, is less than 5%.

Investigating the Seismic Behaviour

The Effect of Splitting on Periods

Fig. 7 demonstrates the effect of splitting on first mode's periods of structures. It would appear that increasing the amount of splitting results in 5.4% increase in period. This is expected to stem from the flexibility that the middle column (shared by the two parts) introduces in the structure.

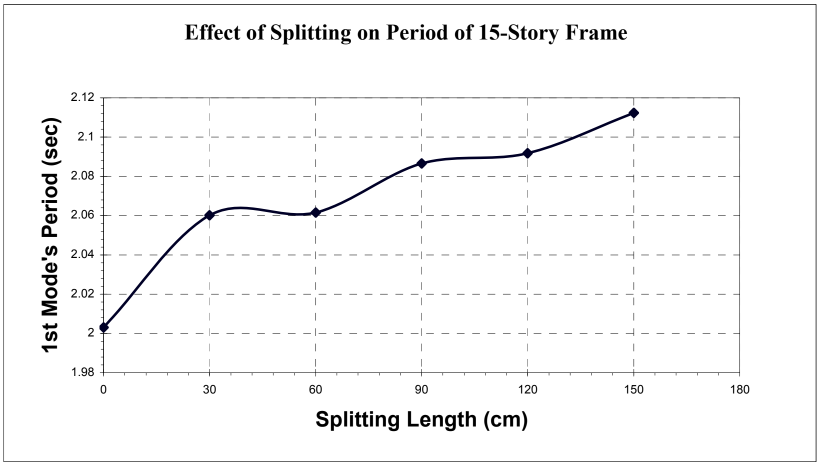


Figure 7. Effect of splitting on fifteen-storey frame's period.

The Effect of Splitting on Distribution of Base Shear

As Fig. 8 illustrates, increasing the magnitude of the split dimension concentrates the shear force on higher level foundations. In other words, splitting transfers the shear of base columns from lower to higher level. For instance, increasing the distance of levels in the five-storey frame resulted in 60% increase in shear force proportion of higher-level foundations.

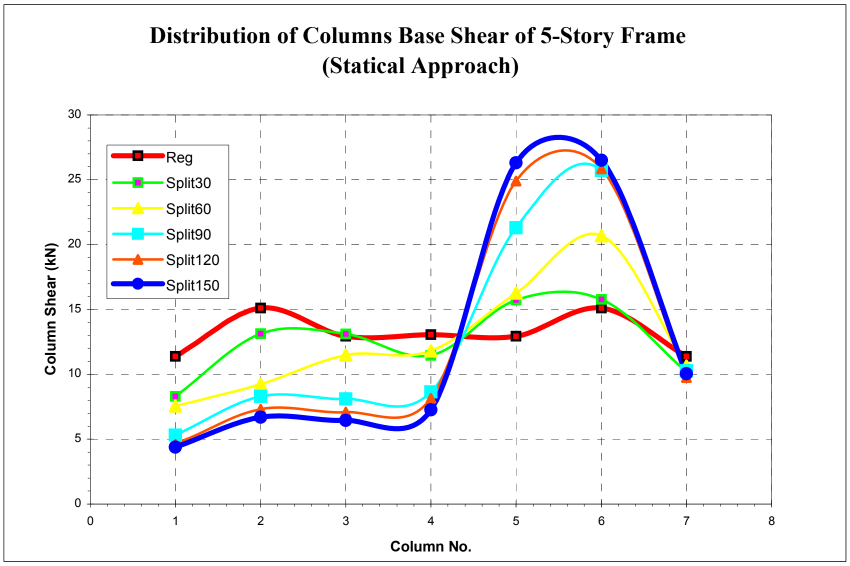


Figure 8. Effect of splitting on distribution of base shear among foundation levels.

The Effect of Building Height on Distribution of Base Shear

As it is shown in Fig. 9, the significant effect of frame height on the distribution of base shear is noticeable. Increasing the number of storeys from 5 to 15, affects the distribution of base shear amongst various foundations in a manner that just 12% of the additional base shear is borne by lower level foundations and 88% of it is taken by higher level ones. This phenomenon shows the effects of the two parts of split-level buildings on each other and, as mentioned earlier, separating the two parts, and using static analysis for each part independently (following initial dividing of base shear), is not rational.

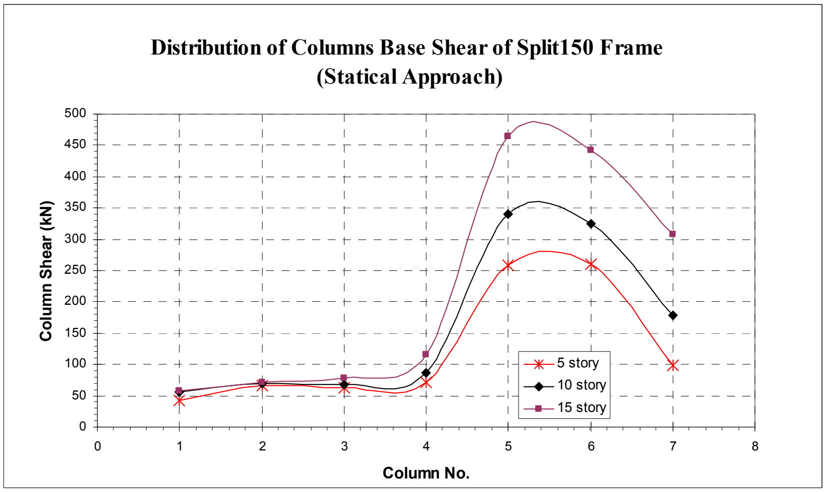


Figure 9. Effect of frame height on distribution of base shear force between upper and lower level foundation.

Conclusions

The following conclusions can be made within the context of studied cases.

1. In applying static loads, the whip force should be divided between the last storeys of the two levels in proportion to their weights.
2. By increasing the splitting distance in the fifteen-storey frame, the period is increased by 5.4%. It shows that the reduced stiffness of common columns makes the building more flexible.
3. By increasing the splitting distance from 0 to 150 cm in five-storey frames, the share of base shear from the higher level foundation increased by 60%.
4. By increasing the number of storeys from 5 to 15, 12% of additional base shear was taken by lower level foundations and 88% of it by higher level ones.
5. The defined parameter of "share of higher level foundations of Base Shear" showed error of less than 5% in the results of the proposed method of distribution of equivalent static loads of split-level buildings. This conclusion clarifies the importance of applying the proposed method instead of dynamic method. This conformity of distribution of static loads and the loads obtained from modal analysis shows that by using the proposed distribution of equivalent static loads, there is no need to use dynamic analysis for split-level frames.
6. More comparative cases should be studied when complex structural geometries are concerned.

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