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INVESTIGATIONS ON VERTICAL STRUCTURAL IRREGULARITIES IN MULTI-STORY STRUCTURES

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ABSTRACT

In this paper, the punitive nature of "Dynamic Analysis", which is included in most contemporary seismic regulations and codes for multi-story buildings, is examined by applying a parametric test procedure. Various types of vertical irregularities are tested on a number of structures and the results are evaluated. Weight (mass), stiffness, strength and geometric irregularities are taken into account. In each case of irregularity, typical multi-story structures are chosen and analyzed by using "Equivalent Static Loads" which are computed according to the final draft of the new "Turkish Seismic Code". The results are then compared to those obtained by the method of "Modal Superposition".

For each typical structure, the ratios of the design bending moments due to the two types of analysis are computed throughout the structure. These ratios, which are called local "Computational Safety Factors" (CSF), are examined and evaluated throughout the critical sections of the structures. The weighted average of these values yields a characteristic value, which is called the overall "Computational Safety Factor", is used in the evaluation of various structural irregularities.

KEYWORDS

Multi-story structures; structural irregularities; earthquake analysis.

INTRODUCTION

In most contemporary seismic regulations and codes for buildings, structural irregularities both in plan and in elevation are required to be taken into consideration in earthquake resistant design procedures. In almost all seismic codes, "Dynamic Analysis" is demanded for several cases of structural irregularities, which is considered as a punitive measure. However, in many cases, the punitive nature of "Dynamic Analysis" seems rather doubtful and open to discussion. In this paper, various types of vertical irregularities and discontinuities are examined by applying a parametric test procedure on a number of structures and the results are evaluated.

Weight (mass), stiffness and geometric irregularities together with in-plane vertical discontinuities are taken into account. In each case of irregularity, typical multi-story structures are chosen and analyzed by using equivalent static loads which are computed according to the latest "Turkish Seismic Code" regulations. The results are then compared to those obtained by the method of "Modal Superposition". The idealized acceleration spectrum diagram used in the modal analysis is shown in Fig. 1. This spectrum diagram, which is also in accordance with the Turkish Seismic Code, is an idealised version of "Housner's Acceleration Diagram."

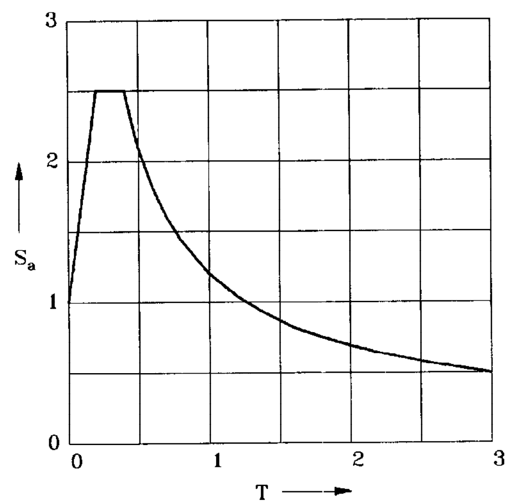

Fig. 1. Idealized spectrum diagram

For each typical structure, the ratios of the design bending moments of structural components due to the two types of analysis are computed throughout the structure. The weighted average of these ratios yields a characteristic value which is called "Computational Safety Factor" (CSF) which is used in the evaluation of various structural irregularities. The weighting factor in computing the CSF values, is taken as the absolute value of the corresponding end force.

TYPICAL FRAMED STRUCTURE

The geometric properties, masses and static equivalent loading of a typical 16-story frame is shown in Fig. 2. Beam cross sections are constant throughout the structure. This frame may be considered as representing a 16-story framed structure.

The summarized results of static and dynamic analyses are shown on the diagrams in Fig. 3, where the design values of beam end moments and column base moments are plotted along the height of the structure. It is seen that, at all the critical sections of the structure, static loading yields higher values compared to the dynamic analysis. The overall weighted average of the ratios of the bending moments due to the two types of analyses, which is called "Computational Safety Factor" (CSF) is computed as 1.44 .

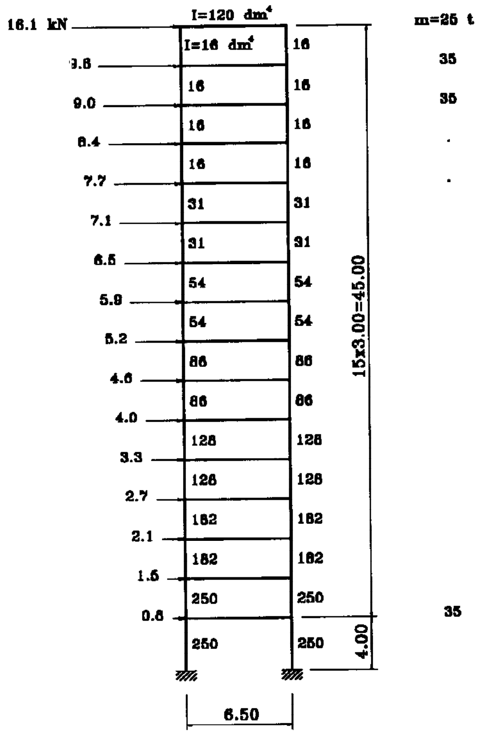

Fig. 2. Typical framed structure

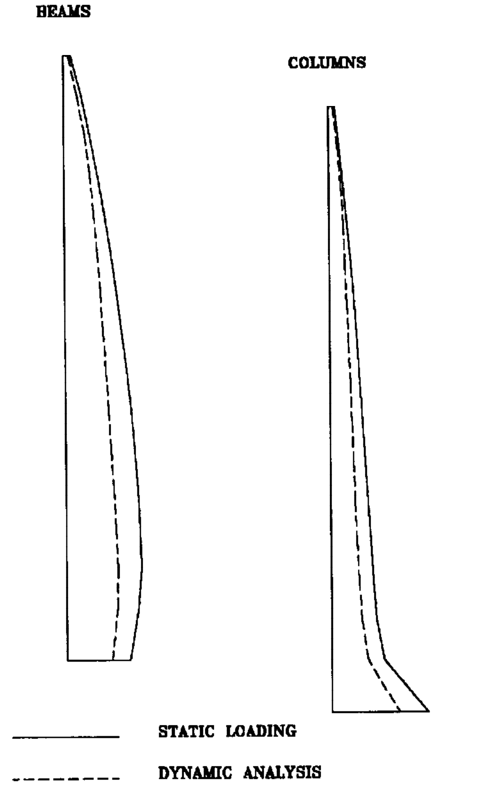

Fig. 3 Bending moments at critical sections

VARIOUS TYPES OF STRUCTURES

The above mentioned analysis procedure (CSF Analysis) is applied to a number of 16-story structures with varying characteristics and the results are summarized on Table 1. The characteristics of the "Frame with Rigid Columns" are identical with the "Typical Frame" except that the column rigidities are doubled. The columns of the "Frame with Uniform Columns" are constant (182 dm^4) throughout the structure. "Structural Wall" and "Wall with Openings" represent multi-story structures with only structural walls as lateral load resisting elements. Lastly, "Structure with Frames and Walls" represents an actual high-rise building. The details of the characteristics of the last three types of structure are not included herein for the sake of brevity.

Table 1. CSF values for regular structures

Structure Type	CSF Values
Typical Frame	1.44
Frame with Rigid Columns	1.32
Frame with Uniform Columns	1.34
Structural Wall	1.40
Wall with Openings	1.28
Structure with Frames and Walls	1.39

Inspection of Table 1, shows that all types of structures have slightly varying computational safety factors greater than 1. It may be concluded that, analysis by using static equivalent forces, is always on the safe side by a factor between 1.3 and 1.4 for regular 16-story structures.

MASS IRREGULARITY

Mass irregularity is induced to the regular structures, by increasing the mass of 12th story by a factor of 3, and the CSF values obtained by CSF analysis are shown on Table 2.

Table 2. CSF values for mass irregularity

Structure Type	CSF Values
Typical Frame	1.53
Frame with Rigid Columns	1.37
Frame with Uniform Columns	1.39
Structural Wall	1.35
Wall with Openings	1.27
Structure with Frames and Walls	1.45

Comparing Tables 1 and 2 shows that, corresponding CSF values do not differ considerably. Moreover, the values on Table 2 are greater than the ones on Table 1 in most of the cases. Hence, mass irregularity does not necessitate any punitive measures.

VERTICAL GEOMETRIC IRREGULARITY (SOFT STORY)

The lowermost stories of the regular framed structures are softened by increasing their heights. For each case, the height increment is so determined that, for static loading, the relative displacement of the lowermost story is more than 1.5 times the relative displacement of the story above.

Table 3.CSF values for soft-story irregularity

Structure Type	CSF Values
Typical Frame	1.47
Frame with Rigid Columns	1.35
Frame with Uniform Columns	1.37

The results of the CSF analysis are shown on Table 3. Here again, the CSF values are of the same order with (and greater than) the corresponding ones on Table 1. Hence, this type of irregularity also does not necessitate any punitive measures.

VERTICAL GEOMETRIC IRREGULARITY (WEAK STORY)

The lowermost story of the "Wall with Openings" is weakened by replacing the wall portions with columns. CSF analysis of the weakened structure yields

$$CSF=1.19$$

which is somewhat low compared with the corresponding CSF value of 1.28 of the regular structure. However, it has been observed that, all individual CSF values throughout the structure are still higher than unity. Hence, even for this type of structure, "Dynamic Analysis" does not seem to be a sufficient punitive measure. On the other hand, the complex idealization techniques required for the analysis along with the poor seismic performance of this type of structures is too serious matter to be ignored. Therefore, for structures with weak stories, certain constructive and punitive measures other than "Compulsory Dynamic Analysis" should be considered in seismic regulations.

VERTICAL DISCONTINUITY (SET-BACK)

Vertical discontinuity is considered as an important case of irregularity in most of the contemporary earthquake regulations. In order to test the behaviour of this type of structures, the regular framed structures are modified by adding two more spans to the lowermost 4 stories as shown in Fig.3.

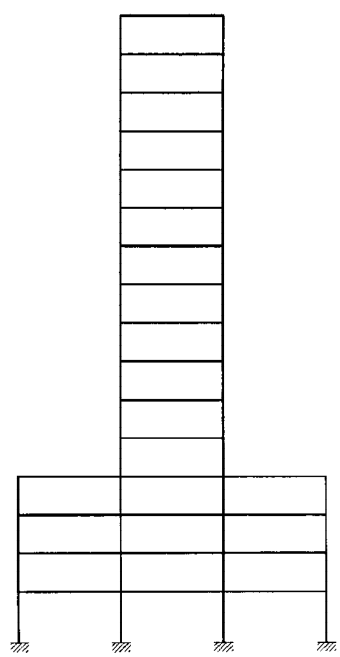

Fig. 3. Set-back frame

The results of the CSF analysis are shown on Table 4. Here again, it is seen that, CSF values are of the same order with the ones in Table 1. However, it has been observed that, in certain critical sections, local CSF values are slightly less then unity. Hence, this type of irregularity needs further parametric investigations.

Table 4. CSF values for set-back irregularity

Structure Type	CSF Values
Typical Frame	1.39
Frame with Rigid Columns	1.38
Frame with Uniform Columns	1.31

STRUCTURES WITH VARIOUS STORY NUMBERS

The results of CSF analyses given above, are for the typical story number of 16. The same procedure is applied to structures with similar characteristics, by changing the number of stories between 8 and 24. The results obtained by this parametric study for framed structures, i.e., the variation of CSF values are shown in Fig. 4.

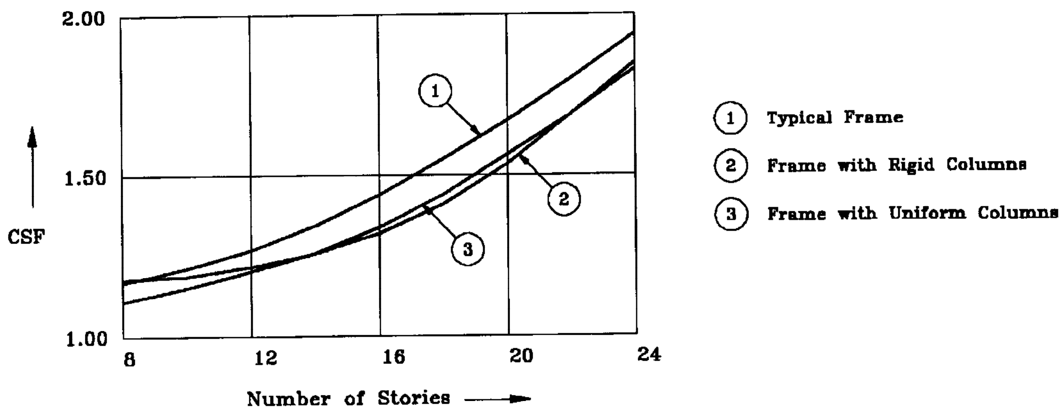

Fig. 4. CSF values for varying story numbers

Similar parametric studies for other types of structures as well as for the cases of irregularity also have been carried out, whose details have not been included for the sake of brevity. It is seen that, for all cases, CSF values increase considerably by the number of stories, i.e., structures with greater number of stories have greater safety factors when designed according to static equivalent forces.

CONCLUSIONS

By the application of the above described parametric numerical test procedure, a large variety of structures have been tested and a number of interesting results for both regular and irregular structures have been produced. The most important of these results are listed in the following:

1. The computational safety factor, which is induced by the application of the static equivalent loads is greater than unity for all the investigated cases. Hence, it is concluded that, "Static Equivalent Loading" is both safe and practical for a large variety of structures,

2. For all cases of vertical irregularity, individual CSF values at almost all critical sections of the structure, as well as the overall weighted average CSF values are found to be greater than unity. Thus, it is shown that, "Dynamic Analysis" is not a "Punitive Measure" for any kind of vertical irregularity.

3. Even for the structures with "Weak Story", which is found to be the most "Dangerous" case of irregularity, dynamic analysis does not seem to be a sufficiently punitive measure. For this type of structures, other structural and punitive measures should be considered in seismic regulations.

4. It is observed that, for both regular and irregular cases, CSF values increase considerably by the number of stories, i.e., structures with greater number of stories have greater safety factors when designed according to static equivalent forces. Hence, for structures with large number of stories, "Compulsory Dynamic Analysis" appears to be an economic rather than a punitive measure.

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