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Limitation of codified torsional provisions

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ABSTRACT: An assessment on the accuracy and applicability of the torsional provisions of the National Building Code of Canada 1985 is conducted through the study of five eccentric multistory buildings. These examples represent varied classes of regular and irregular structures. NBCC 1985 suggests that the torsional provisions apply only when the centers of mass and centers of rigidity lie on two vertical axes. From the current study, it is shown that one should interpret this specification as a sufficient, but not a necessary condition for the code procedures to apply. Until the necessary conditions are established, dynamic modal analysis remains the most reliable tool for estimating the torsional seismic effect on irregular eccentric multistory buildings.

1 INTRODUCTION

One important aspect in multistory building design is the effect of lateral loads on building performance. The lateral loads can be caused by wind or earthquake ground motions. Though such enviromental load effects are dynamic in nature, they are often prescribed in building codes as sets of equivalent static design loads. If the building is torsionally unbalanced, due to asymmetry in geometry, stiffness or mass distribution, torsional response will result causing additional shears and deformations in the lateral resisting system.

To allow for the torsional effect caused by ground shaking on buildings, most seismic torsional provisions in building codes make use of the eccentricity concept. It is required by building codes that buildings be designed for additional torques applied simultaneously with the lateral loadings. The torque load to be applied at a particular floor will be given as the product of the lateral load resultant and the design eccentricity at that floor. The design eccentricity will be a function of the structural eccentricity which is defined as the distance between the center of rigidity at a level and the applied load resultant at that level. The inertial lateral forces will act through the mass centers of the floors which can be computed readily. Thus the problem of determining the design eccentricities reduces to locating the center of rigidity at each floor. Further, it is stated explicitly in the National Building Code of Canada 1985 (NBCC 1985) that the seismic torsional provisions are applicable to eccentric buildings with centers of mass and centers of rigidity falling on two vertical axes. Therefore, in applying specifically the torsional provisions of NBCC 1985 for building design, a knowledge of the rigidity centers of the building is required to :

1. determine whether the torsional provisions are applicable; and assuming the provisions are applicable, to
2. determine the structural eccentricities, thus the design eccentricities and finally the design torque at each story of the building.

A procedure was developed by Cheung and Tso (1986) for determining the centers of rigidity for multistory buildings. With eccentricity defined, a study to evaluate the use of the eccentricity concept as employed by NBCC 1985 to simulate the torsional seismic effect on asymmetrical multistory buildings will be conducted. This paper presents the findings of the study. Five sample buildings are considered, representing varied classes of regular and irregular structures. For each building, the centers of rigidity and floor eccentricities are first calculated. The design torsional moments as specified

Table 1. Rigidity distribution of resisting elements.

Bldg.	Floor	Element 1	2,3	4	5,6
A	1/F-9/F	4.25EI[a]	4.25EI	4.25EI	8.85EI
B	1/F-6/F	4.25EI	4.25EI	4.25EI	8.85EI
	7/F-9/F	4.25EI	4.25EI	2.83EI	8.85EI
C,D	1/F-9/F	EI	GA[b]	EI	2.08GA
E	1/F-6/F	4.25EI	4.25EI	4.25EI	8.85EI
	7/F-9/F	-	4.25EI	-	8.85EI

a $EI = 9.72 \times 10^3$ MN-m^2.
b $GA = 0.11 \times 10^3$ MN.

Table 2. Mass properties.

Bldg.	Floor	Mass (Mkg)	Polar mass (Mkg.m^2)
A,B,C,D	1/F-9/F	0.73	3.06
E	1/F-6/F	0.73	3.06
	7/F-9/F	0.37	0.61

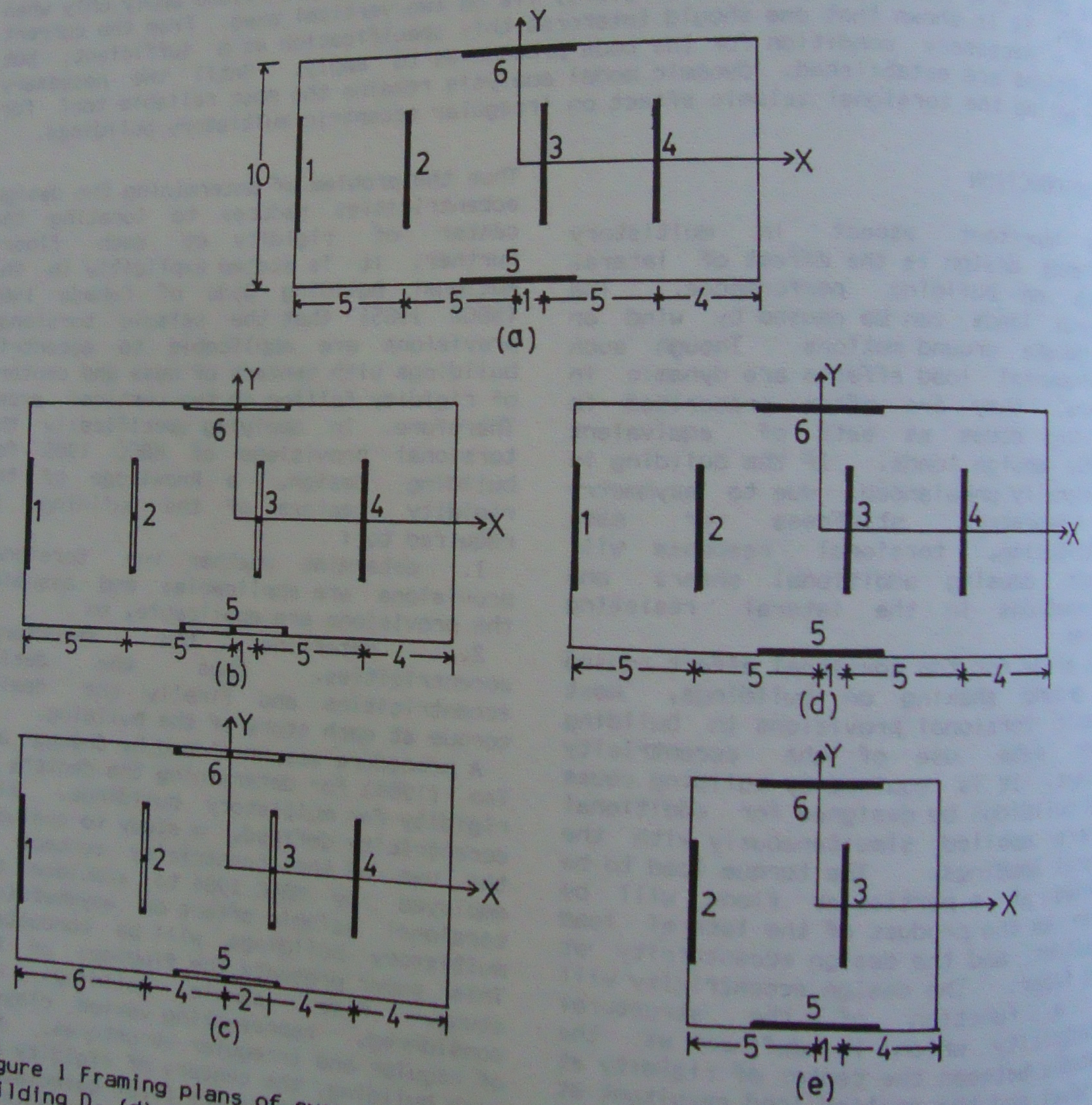

Figure 1 Framing plans of example buildings (a) buildings A and B, (b) building C, (c) building D, (d) base of building E, (e) tower of building E

in NBCC 1985 will then be computed. Finally, the design shears on representative lateral resisting elements are determined. The design shear distribution will be compared to those computed using dynamic modal spectrum analysis. Through such an exercise, the accuracy and applicability of the torsional provisions of NBCC 1985 can be assessed.

2 A PROCEDURE TO COMPUTE FLOOR ECCENTRICITY

To determine the structural eccentricities of a multistory eccentric building subjected to given lateral load distribution, it is necessary to locate the center of rigidity at each floor. The centers of rigidity of a multistory building are defined as the set of points located at floor levels such that when the given distribution of lateral loading passes through them, no rotational movement of the building will occur. Base on such a definition, a procedure for locating the centers of rigidity for multistory buildings was developed which involves only the use of standard plane frame program. Computer model of the building are to be created by lining up all resisting elements in one principal direction and connect them together at floor levels by axially rigid beam elements with hinged ends to simulate rigid diaphragm actions. By analysing such model subjected to the prescribed lateral loads by means of a plane frame program, the resisting shear distribution and thus the floor loads in the resisting elements can be obtained. The coordinate position of the rigidity center at each floor will be given by the ratio of the sum of the first moments of the resisting floor loads about the reference axis and the total applied floor load at that floor. It is shown that the centers of rigidity will be in general load distribution dependent and are different from the stiffness centers. It is for proportional framing structures that the rigidity centers will fall on a vertical line.

3 EXAMPLES

Five example buildings are chosen to demonstrate the variation of the rigidity centers under given applied load distribution. Each of these buildings is nine story high, having an uniform floor height of 3m. Except for the tower portion of the setback example structure, the basic floor plan will be rectangular in shape measuring 10m by 20m. The arrangement of the resisting elements are such that each building is symmetric in the x direction and eccentric in the y direction, as shown in figure 1. Building A will have uniform wall elements to resist the lateral loads. Therefore, building A is a building with proportional framing, and the centers of rigidity can be determined on a per floor basis. Building B has identical floor framing plan as building A except that the rigidity of wall 4 at the top three floors is reduced to 2/3 that at the base. Building B will represent the class of buildings with near proportional framing. Buildings C and D are two eccentric uniform wall-frame buildings. Two rigid frames provide the required lateral resistance in the x direction. In the y direction, two walls and two frames are used as resisting elements. Further, the beams in the frames are considered very stiff in relation to the columns so that each frame can be treated as a shear beam for computational purposes. The rigidity distribution and layout of the walls and frames are chosen such that there will be significant degree of wall-frame interaction, both laterally and torsionally. For building C, the stiffness center of the wall system coincides with the stiffness center of the frame system. For such a building, the rigidity centers will fall on a vertical line. Thus building C represents a special class of uniform wall-frame structures. Building D is similar to building C except that the frame system in the y direction is shifted 1m to the right from its original position. Due to the change in layout, the stiffness centers of the wall and frame system no longer align. Building D will represent a more general class of uniform wall-frame buildings. Finally, building E is an eccentric setback building with a single setback at the 6th floor. The framing plan of the base structure is identical to that of building A. For the tower structure, the floor plan dimension in the x direction is reduced by 5m on each side of the mass center. Walls in the x direction will extend from the base into the tower. However, only wall elements 2 and 3 provide lateral resistance in the y direction. Setback structures are often considered as irregular structures with scattered rigidity centers. However, for this building, the stiffness center of the tower lateral resisting system in the base and the aligns with that at the base and the

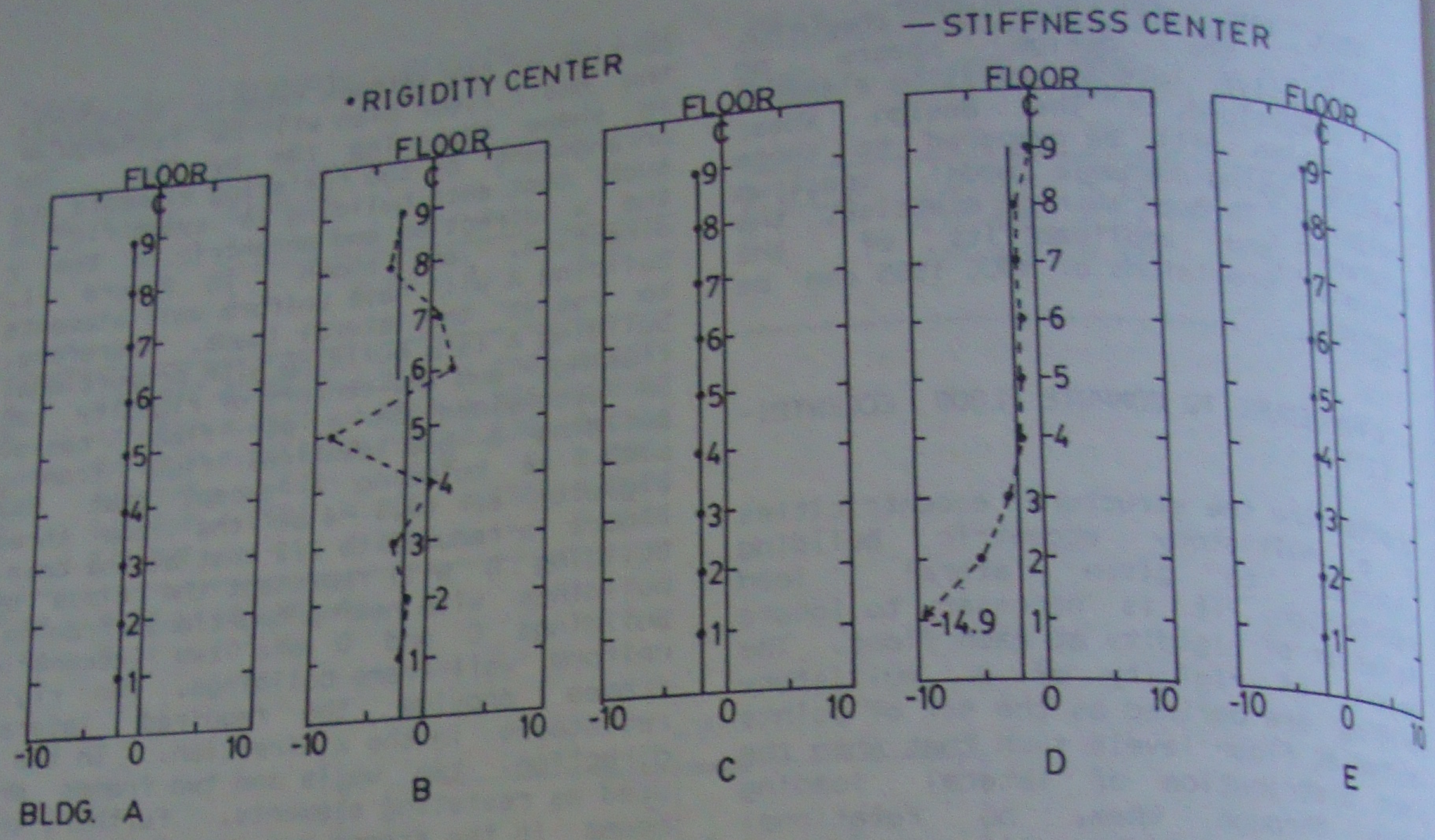

Figure 2 Distribution of rigidity and stiffness centers

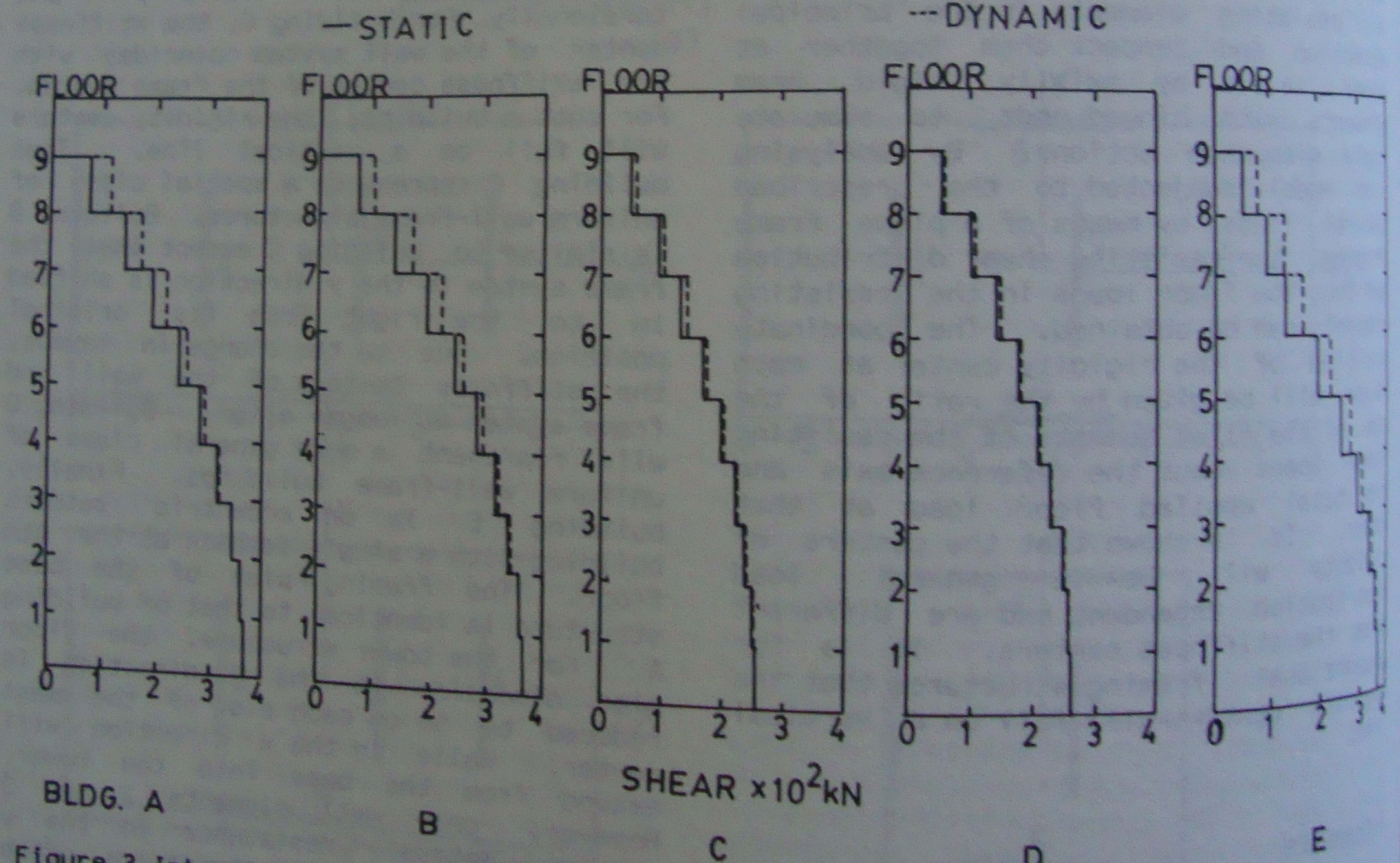

Figure 3 Interstory shear envelopes

rigidity centers of the building will fall on a vertical line. Thus building C represents a special class of setback structures. Of the five sample structures, buildings A and C can be considered as the basic structures. Buildings B, E and D will be derivatives of the basic structure A and C respectively. All buildings will have mass centers located on a vertical straight line. The distribution of the rigidities of the resisting elements is summarized in table 1.

The sample buildings will be subjected to the static seismic load distribution as suggested in NBCC 1985. The locations of the centers of rigidity of each building are determined by the procedure as outlined in the last section. The centers of stiffness of the resisting elements are also determined, on a per floor basis assuming each floor behaves as a single story building. The distributions of the rigidity and stiffness centers of the example buildings are shown in figure 2. Building A, having a proportional framing arrangement, is shown to have centers of rigidity lying on a vertical line, as expected. Despite the fact that building B differs only in a slight manner from building A, it nonetheless is a building of non-proportional framing, and there is considerable scattering of the rigidity centers. The rigidity centers are scattered on both sides of the mass centers. With coincident stiffness centers of the wall and frame system, the rigidity centers of building C also fall on a vertical axis. A shift in the position of the frame system of building D leads to a scattering of the rigidity centers. However, unlike building B, the rigidity centers are confined to one side of the mass centers. Despite the fact that building E is an eccentric setback structure, its rigidity centers remain align on top of each other along the height of the building.

It can be seen that the rigidity centers are in fact sensitive quantities, as demonstrated by buildings B and D. If a regular stucture is defined as one having mass and rigidity centers falling on two vertical axes, then buildings A, C and E will belong to such category. On the other hand, buildings B and D will be irregular structures. For regular structures without setback, the torsional provisions of NBCC 1985 guarantee to provide a resonable estimate of the seismic torsional effect. However, the code procedures may or may not work for irregular structures. For setback structures in general, the code suggests they are best handled by the dynamic method. An investigation into this aspect will be given in the following section.

4 SEISMIC RESPONSE COMPARISON - BUILDING CODE APPROACH VERSUS DYNAMIC ANALYSIS

The seismic responses of the five buildings as predicted by the static procedures of NBCC 1985 will be compared to that from dynamic modal spectrum analysis. For spectrum analysis, the responses of the first five modes are combined in a square root of the sum of the squares manner to give the total response since the effect of cross modal coupling is not important for the buildings studied. All buildings are assumed to be located in Vancouver with an acceleration and velocity related zone of both being 4 in this case. The mass properties of the sample buildings are listed in table 2. The fundamental periods of vibration of buildings A through E are 0.6, 0.6, 0.6, 0.58 and 0.46 respectively. To make the comparison meaningful, the results based on spectrum analysis are normalized so that the dynamic base shear in the building is identical to the base shear determined using the static code procedures.

Shown in figure 3 is a comparison of the interstory shear force envelopes of the five buildings. The distributions based on NBCC 1985 provisions and the five mode dynamic response show very little difference. Thus the code procedures are capable of providing good estimates of interstory shear distribution, even for the setback sample structure.

Regarding torsional effect, the resisting element on the same side as the mass centers relative to the centers of rigidity is identified by the code as most susceptible to torsion. Thus, for the sample buildings, the most critical element will be wall 4 which is furthest away from the rigidity centers. The design eccentricity e_x appropriate for this element is given in NBCC 1985 as $e_x = 1.5e + 0.1D_n$. e is the structural eccentricity and D_n is the plan dimension of the building in the x direction. In this paper, emphasis will be placed in evaluating the accuracy of the above equation for determining shear distribution in the resisting elements. The two basic structures (buildings A and C) will have an e/D_n ratio of 0.1. An e/D_n ratio of 0.1 represents buildings with moderate eccentricity. The structural eccentricity e is constant along the height of the two buildings.

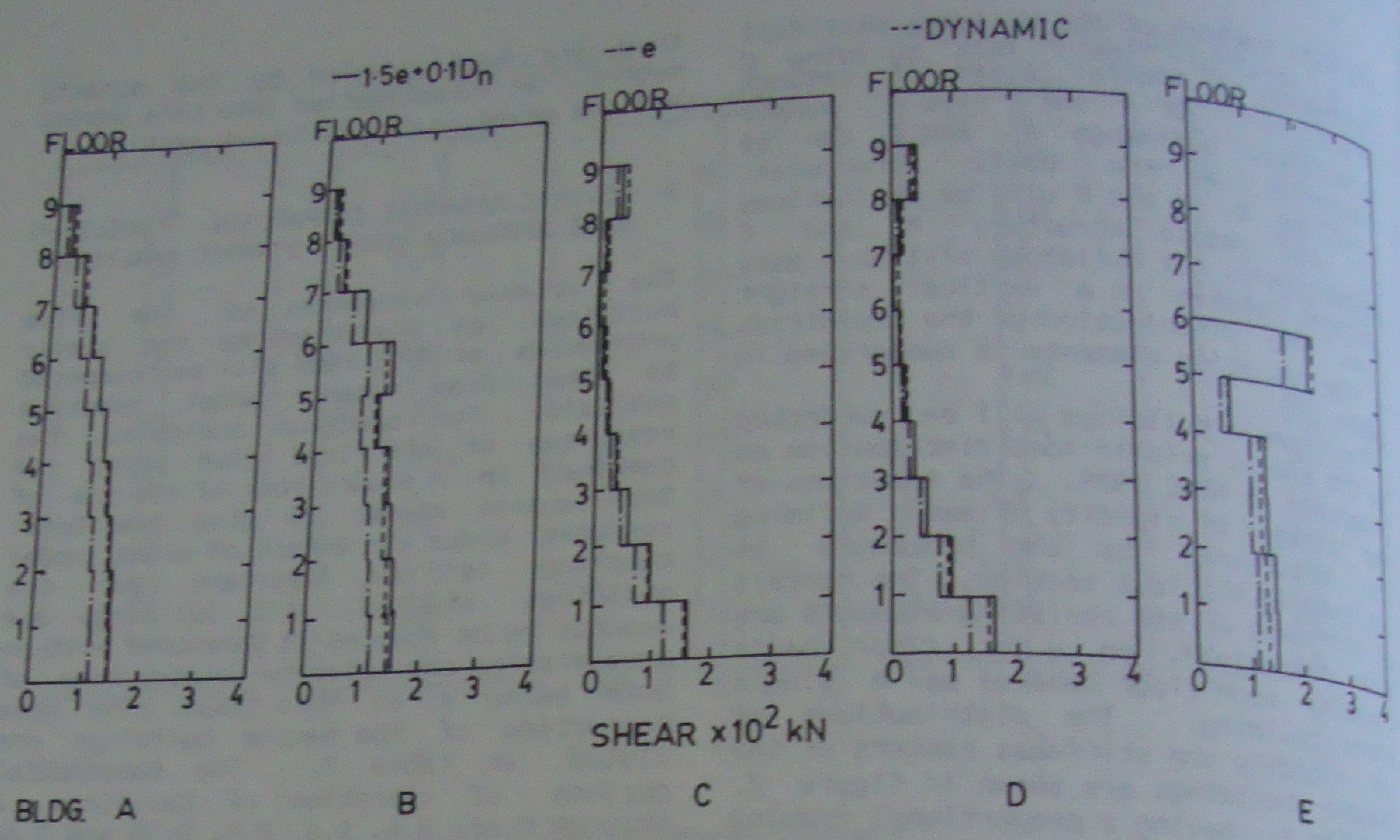

Figure 4 Shear envelopes of element 4

Even with applied lateral loads and structural eccentricities determined, complications still arise in applying the torsional provisions. This is because of the possible scattering of the rigidity centers on both sides of the mass centers along the height of the building, as evident by building B. One would encounter both positive and negative values of floor eccentricities which in turn makes the interpretation of the code provisions difficult. One simple, but not strictly correct way is to treat the center of rigidity at each floor to be the stiffness center at that floor. The distribution of stiffness centers are represented by the solid lines in figure 2. The eccentricity thus measured with respect to the stiffness center will be used in place of the true floor eccentricity to determine the design eccentricity for building B.

Shown in figure 4 are the shear envelopes of wall 4 of each building. Three curves are shown in each plot. They are calculated based on (i) dynamic modal analysis; (ii) the code design eccentricity formula; and (iii) the actural structural eccentricity. For the latter case, the design lateral loads will be applied through the centers of mass of the building. The shear envelopes determined by dynamic analysis represent the best estimate of the shear distribution in an element. The shear envelopes based on code provisions are an attempt to approximate the dynamic shear envelopes. It can be seen from figure 4 that the code procedures lead to results which are in good agreement with that from dynamic analysis for all buildings. Since buildings A and C have mass and rigidity centers falling on two vertical lines, such an agreement is anticipated. Despite the crude nature by which the floor eccentricities are determined for building B, and despite the dispersion of rigidity centers for building C, the code procedures still provide good estimation of shear distribution. With reasonable approximation of lateral force distribution by the code, close agreement in shear distribution is also observed for building E. It can be seen that the shear distributions computed using the true eccentricities are considerably smaller than that from dynamic analysis. Such discrepancies can be attributed to the dynamic magnification effect. The code attempts to approximate such effect through the use of design eccentricity instead of the actual eccentricity for computing the torsionl moment and produces favourable results for the buildings studied.

5 CONCLUSIONS

By means of examples, the locations of the centers of rigidity and the ability of the codified torsional provisions to estimate the design shear envelopes in five eccentric buildings are presented. It is shown that for regular buildings without setback, the code procedures do provide good estimates of the seismic torsional effect. For setback and irregular structures with rigidity centers scattered from a vertical axis, the code procedures may still deliver good results but no warranty can be assumed from the code. Therefore, one should interpret that the condition of centers of mass and centers of rigidity located along vertical axes to be a sufficient, but not a necessary condition for NBCC 1985 torsional provisions to be applicable. Further, it is shown that the rigidity centers are sensitive quantities. It would be reasonable to expect that the scattering of rigidity centers will exist in most buildings. Therefore, requiring the rigidity centers to be on a vertical line may not be the best criterion to determine whether code provisions for torsion are applicable to a particular building. When in doubt, the evaluation of torsional effect is best done by means of dynamic analysis.

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LIST OF SYMBOLS

D_n = plan dimension of building in the direction of computed eccentricity;
EI = flexural rigidity of wall;
e = structural eccentricity;
e_x = design eccentricity; and
GA = shear rigidity of shear beam.

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