CLARIFICATION OF THE REQUIREMENTS IN THE NATIONAL BUILDING CODE FOR SCALING OF SEISMIC FORCES OBTAINED BY DYNAMIC ANALYSIS

Based on reviews of building permit applications, an Ontario municipality recently reported to PEO that some professional engineers have interpreted specific building code requirements in different ways, notably sentences 8, 9 and 10 in "Article 4.1.8.12 Dynamic Analysis Procedure" of the National Building Code of Canada. This could result in over-conservative designs. Consequently, PEO's Professional Standards Committee invited two building code experts to clarify this issue.

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The National Building Code (NBC) requires the use of dynamic analysis procedure to determine the design seismic forces, except for situations in which the equivalent static force procedure is adequate, as described in Article 4.1.8.7. The dynamic analysis method provides a more accurate estimate of the design base shear than the equivalent static force procedure, provided the structural model used in the analysis is correct. However, such a model often tends to be more flexible than the actual structure because it does not account for the stiffness contributed by non-structural elements. Because the design spectral response acceleration decreases with flexibility, the base shear V_d determined from dynamic analysis tends to be smaller than what the actual structure experiences. NBC Sentence 4.1.8.12.(8) addresses this concern by requiring that when the calculated value of V_d is less than 0.8V, with V being the design base shear determined by the equivalent static procedure, V_d should be taken as equal to 0.8V.

For irregular structures, the requirement related to the minimum value of design shear is more stringent. This is because in such structures, the model used for the dynamic analysis may not fully capture the impact of irregularities in the distribution of ductility demand. Thus, NBC Article 4.1.8.7 requires that whenever the structure is irregular, V_d should be taken as no less than V.

For regular structures, whenever V_d is less than 0.8V, a scale factor equal to the ratio of 0.8V to V_d must be calculated. This factor is applied to the forces in the structure that are associated with V_d to obtain the design forces. For irregular structures, the scale factor is equal to the ratio of V to V_d.

In determining the scale factor, V and V_d should both be obtained from the analyses of the same structural model. For calculating V, it is invariably assumed that the structure undergoes displacement only in the direction of the earthquake; therefore, the model used in determining V_d should also be similarly constrained. This is automatically ensured for a structure in which the mass and stiffness centres are coincident so that the structure is torsionally balanced. However, when the shear V_d is determined from a three-dimensional analysis of a torsionally eccentric structure, the coupling of lateral and torsional response can produce a response that is considerably lower than that for torsionally balanced structure. Therefore, in such cases, the requirement that V_d be not less than 0.8V or V would be overly conservative and provide a scale factor that is significantly larger than what would be required to account for the stiffness contributed by non-structural elements. A method of determining the

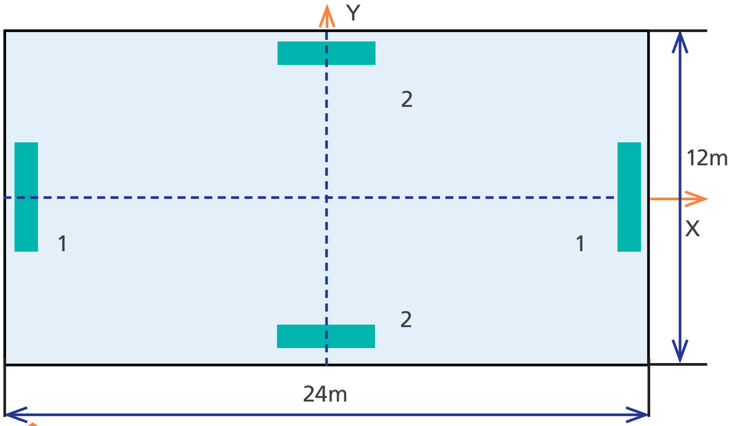

Figure 1a: Torsionally balanced building

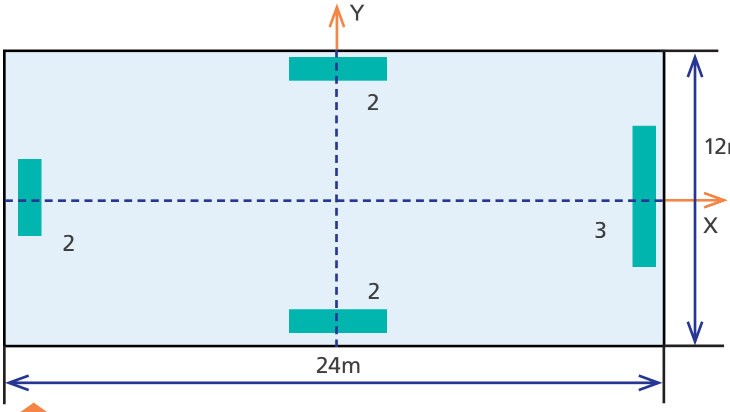

Figure 1b: Torsionally unbalanced building

scale factor that is consistent with the intent of NBC is to use V_d obtained from the analysis of a model in which the rotations of floor and roof are restrained so that there is motion only in the direction of the earthquake. This scale factor can then be applied to the design base shear, V_d and the member forces and displacements determined from the dynamic analysis of a model in which the floor and roof are allowed to rotate. The method is illustrated by the folowing example.

EXAMPLE

Consider the three-storey structure shown in Figures 1a and 1b on page 18. The building mass is concentrated at the floor levels, and all floors are assumed to be rigid. The floor height is four metres in both cases. The other properties are:

Floor masses	176.0 tonne
Floor mass moment of inertia	10,560 tonne.m^2
Shear wall ID 1	4.236 m × 0.25 m
Shear wall ID 2	3 m × 0.25 m
Shear wall ID 3	5 m × 0.25 m
Rd = 3.5	
Ro = 1.6	
I_E = 1.0	

The moment of inertia of each wall is taken as 0.35 times the gross moment of inertia, and shear deformation is ignored. The building in Figure 1a is torsionally balanced, while that in Figure 1b is torsionally unbalanced. The total stiffness of the two buildings in the Y direction is identical; however, in Figure 1a it is equally distributed among the two walls, while in Figure 1b it is unequally distributed.

The uniform hazard spectrum for the site has: Sa(0.2) = 0.66 g, Sa(0.5) = 0.66 g, Sa(1.0) = 0.34 g, and Sa(2.0) = 0.18 g.

Note that both buildings are considered regular, as per NBC. The building in Figure 1b is torsionally unbalanced but does not have the Type 7 Irregularity (Torsionally Sensitivity)

Analysis of the building in Figure 1a

A response spectrum analysis of the building of Figure 1a for an earthquake in Y direction gives a fundamental period T_a = 0.433 s and an elastic base shear V_e = 2954.6 kN. After the short period cap is applied the design elastic shear V_{ed} = 2600 kN, hence the design base shear is V_d = 2600/(3.5 × 1.6) = 464.3 kN. The design base shear obtained from dynamic analysis V_d must be checked against the design shear V obtained by equivalent static analysis.

For an equivalent static analysis of the building, the empirical period determined as per code is 0.322 s. The code permits the use of the dynamic period 0.433 s, since it is less than two times the empirical period. After applying the short period cap, the elastic base shear is 3315.0 kN, and the design shear V is 3315/(3.5 × 1.6) = 592.0 kN

The building is regular. The Code Sentence 4.1.8.12.(8) requires that for a regular building, the design base shear V_d must be no less than 0.8V or 0.8 × 592.0 = 473.6 kN. Thus, to obtain the design base shear the dynamic base shear must be increased by a factor of 473.6/464.3 = 1.02.

The final value of V_d is, therefore, determined as 473.6 kN.

Analysis of the building in Figure 1b

Because the total stiffness in the Y direction is the same as that for Figure 1a, the design shear V obtained from equivalent static analysis of the building in Figure 1b is the same as for the building in Figure 1a, i.e. 592.0 kN. The building is regular. Hence, as in the case of building in Figure 1a, the design base shear V_d calculated from dynamic analysis must be no less than 0.8V or 0.8 × 592.0 = 473.6 kN.

Now let us look at the determination of scale factor for this building. The building is torsionally unbalanced. Assuming that it is not restrained against torsion, a 3D response spectral analysis must be carried out. The coupling between torsional and lateral response increases the period to 0.599 s and reduces the elastic base shear after short cap adjustment, V_e, to 2146.6 kN. Correspondingly, V_d = 2146.6/(3.5 × 1.6) = 383.2 kN. If this value of V_d is used, the scale factor works out to V/ V_d, i.e. 473.6/383.2 = 1.23. As explained in this article, this is a conservative estimate of the scale factor.

Considering that the scaling is carried out to the value of design shear, V, determined from equivalent static analysis, a model that is consistent with that used for determination of V must be used. This is accomplished by restraining the model against torsion. The analysis of such a model will give the values of elastic base shear, V_e and design base shear V_d as 2954.6 kN and 464.3 kN, which are the same as for model in Figure 1a. Therefore, the scale factor V/V_d, by which V_d should be increased again works out to 1.02, the same as the value for the building in Figure 1a.

The value of V_d after scaling, therefore, remains unchanged at 473.6 kN. As explained in the article, this is consistent with the intent of the code.

DESIGN FORCES

The design forces for the building in Figure 1b are determined by scaling the forces obtained from the response spectrum analysis of torsionally unrestrained model. Once again, the scale factor is based on the values of V_e and V_d obtained using a model restrained against torsion, i.e. V_d/V_e = 473.6/2954.6 = 0.1603. It may be noted that such scaling automatically takes all of the following into account: (1) scaling up of the design base shear V_d by the factor 1.02 to 473.6, (2) reduction for short period cap, and (3) reduction by R_d and R_o. **e**

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