TORSIONAL PROVISIONS IN BUILDING CODES

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SYNOPSIS

A study is made on the accuracy of the static code provision on torsional effect, with special reference to the National Building Code of Canada 1977 (NBC 77). A uniform frame type monosymmetric twelve story building is used as an example. The static story torque is compared with the dynamic torque computed using the response spectrum technique as outlined in the Commentary K of NBC 77. It has been found that for a building with uniform eccentricity the static code torque estimate is good if the effect of sympathetic coupled torsional-lateral resonances is small. At sympathetic coupled resonance, the static code torsional provision underestimates the story torque by a factor of two. Also, it is shown that for buildings with large eccentricity, sympathetic resonance is unlikely to occur and the current NBC requirement of doubling the computed torque for design is a very conservative requirement.

RESUME

Une étude est effectuée pour étudier l'effet de torsion sur les bâtiments, tel que décrit par la méthode statique du CNB-1977. Un cadre de douze étages est présenté comme exemple. La torsion obtenue par la méthode statique est comparée avec la torsion calculée par la méthode dynamique telle que présentée dans les commentaires K du CNB-1977. Dans le cas où l'effet d'interaction latérale avec la torsion est faible, la méthode statique est fiable dans ses prédictions de la torsion. Cependant lorsque l'interaction est prononcée, l'effet de torsion pourrait être sous-estimé par un facteur de deux. Par contre pour les bâtiments où l'excentricité est importante, l'interaction devient peu probable et par conséquent le dédoublement de la torsion devient alors trop conservateur.

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INTRODUCTION

Torsional responses, in addition to lateral responses will result when asymmetrical buildings are subjected to earthquake ground shaking. In design, it is necessary to account for such torsional responses which may induce additional shear forces on the lateral resisting elements of the building. Most seismic codes for buildings recognize this necessity and have made provisions for torsional effects. The most common form of torsional provision is the requirement that an additional loading condition due to torsional moments or torques at each story be considered. The torsional moment at each story is obtained by multiplying the story shear by a quantity termed "design eccentricity". The design eccentricity expressions for a representative sample of seismic codes are given in Table (1). Except for the German code, the design eccentricity expression consists of two parts. The first part takes into account the identifiable eccentricity based on stiffness and mass distribution of the structure and is a function of the structural eccentricity e (the distance between the center of mass and center of resistance). The second part, commonly referred to as "accidental eccentricity", takes into account other factors such as torsional ground motion inputs; and is in general a function of D, the maximum dimension of the story measured perpendicular to the direction of lateral loading. In the German code, a third factor is involved which takes into account the sympathetic resonance effect of torsional and lateral modes of vibration.

Torsional moments calculated according to this format are termed static torques. It is essentially an extension of the static equivalent load procedure in computing story shear. It should be pointed out that under the static equivalent load procedure, for a building of given dimensions and weight, a change of eccentricity e will only affect the torsional moments on the structure, but it will not affect the story shears. This is in contrast to results based on dynamic analysis in which both the shears and torsional moments are functions of the building eccentricities.

In the present paper, a study is made on the accuracy and applicability of the code format in taking the torsional response effect into account. The torsional moment distribution along the height of the building is taken as the parameter for comparison. The static torsional moments are compared to the torsional moments computed by the dynamic response spectrum technique. The Canadian code [1] has been chosen upon which the comparisons are made because it is one of the few codes that allow the dynamic response spectrum technique to be used as an alternative for design calculation. Since the design eccentricity expressions of many countries are similar to that of the Canadian code, comments made, based on the Canadian Code, will also have relevance to other codes as far as static torque computations are concerned.

Particular attention is given to the following guidelines from the Canadian Code [1] and its commentaries [9]. They are: (1) the use of the design eccentricity experession $e_x = 1.5e + 0.05D$ (2), the necessity of doubling the computed torsional moment should the design eccentricity exceed a quarter of the floor plan dimension, and (3) the accuracy of the proposed change in the 1979 NBC code [10] in computing design eccentricities for buildings with eccentric offsets.

MATHEMATICAL MODEL

To study the first two issues as outlined in the previous paragraph, an example building of uniform plan dimensions 100 ft by 100 ft (30 m x 30 m) is considered. The building is taken to have twelve stories, each story has a weight of 1,400 kips (640,000 kg). It is a frame type of building with its behaviour under lateral loading well represented by the shear beam model. The building is assumed to be monosymmetric. In the direction parallel to the axis of symmetry, three values of eccentricity e are considered. They represent buildings with small eccentricity, e/D = 3%, moderate eccentricity e/D = 10% and exceptionally large eccentricity, e/D = 50%, as shown in Fig. (1).

Mathematically, the problem of coupled torsional-lateral response can be expressed in the form

$$\begin{bmatrix} M & Me \\ Me & I_e \end{bmatrix} \begin{Bmatrix} \ddot{\underline{x}} \\ \underline{\theta} \end{Bmatrix} + \begin{bmatrix} K_{xx} & 0 \\ 0 & K_{\theta\theta} \end{bmatrix} \begin{Bmatrix} \underline{x} \\ \underline{\theta} \end{Bmatrix} = - \begin{Bmatrix} [M]\,\underline{1} \\ [M]\,\underline{e} \end{Bmatrix} \ddot{g}(t) \qquad (1)$$

where [M] is a diagonal mass matrix, [Me] is a diagonal matrix with elements Me, $[I_e]$ is the mass polar moment of inertia matrix referring to the center of resistance, $\underline{1}$ is a unity column vector and $\underline{e}$ is a column vector with the eccentricity value e. $\underline{x}$ and $\underline{\theta}$ are the displacement and rotation vectors about the centers of resistance. For uniform shear buildings, the matrices $[K_{xx}]$ and $[K_{\theta\theta}]$ take the form

$$[K_{jj}] = k_{jj} \begin{bmatrix} 2 & -1 & 0 & \cdots & & & \\ -1 & 2 & -1 & \cdots & & & \\ 0 & -1 & 2 & -1 & \cdots & & \\ \cdots & \cdots & \cdots & \cdots & -1 & 2 & -1 \\ \cdots & \cdots & \cdots & \cdots & \cdots & -1 & 1 \end{bmatrix} \qquad (2)$$

The lateral stiffness of the building is tuned so that the uncoupled fundamental lateral period is 1 second. For a given eccentricity, the fundamental uncoupled torsional period is varied in the neighbourhood of the fundamental uncoupled lateral period in order to study the sympathetic resonance effect of torsional and lateral vibrations. The uncoupled torsional period is obtained by considering that the centers of resistance of the building are restrained from moving laterally. As a result, the building performs torsional oscillation about the centers of resistance. Mathematically, the uncoupled torsional periods are obtained from the equation

$$[I_e]\ddot{\underline{\theta}} + [K_{\theta\theta}]\underline{\theta} = 0 \qquad (3)$$

Similarly, the uncoupled lateral periods are obtained by the solution of eqn. (4).

$$[M]\ddot{\underline{x}} + [K_{xx}]\underline{x} = 0 \qquad (4)$$

For each building configuration, the dynamic torsional moments and the dynamic base shear are computed by the modal response spectrum technique, using the 5% damped response spectrum given in Commentary K of NBC 1977. The procedure is well documented in Commentary K and shall not be represented here. The modal responses are then combined in an appropriate fashion to yield the total estimated responses.

To make the comparison between the static and dynamic torque meaningful, the dynamic torques are normalized by a factor equal to the ratio of the static base shear to the dynamic base shear. In other words, the normalized dynamic torque and the static torque can be considered to come from structures having the same base shear, namely the static base shear. In this way, any difference between the static and normalized dynamic torsional moments is due to the computation procedure only.

RESULTS AND OBSERVATIONS

The actual coupled periods of the three buildings, with small, moderate and exceptionally large eccentricity are shown in Fig. (2) as a function of τ, the ratio of fundamental uncoupled torsional period to the fundamental uncoupled lateral period. For simplicity, τ shall be referred to as the period ratio in this paper. The effect of sympathetic coupled lateral-torsional resonance is significant only when the actual coupled periods of each pair of modes are close to each other. In the case of small eccentricity, the actual coupled periods for each pair of modes are close in the neighbourhood when the period ratio τ is near unity. For large eccentricity, $\tau = 1$ is not a good indicator that sympathetic coupled resonance will occur since the actual coupled periods are widely separated at $\tau = 1$. In other words, the effect of sympathetic resonance can become important only when the building has small eccentricity and the uncoupled torsional period is near to the uncoupled lateral period.

For the case of small eccentricity (e = 3%D), a comparison of the static and normalized dynamic torques is shown in Fig. (3). Two static torque curves are shown, corresponding to the Canadian and the German code calculations. The normalized dynamic torque envelope is computed assuming the ratio of the uncoupled torsional to lateral period being identical, i.e., $\tau = 1$. Also, the modal torque contributions are combined in a root sum square (RSS) manner.

It can be seen that all three envelopes have similar shapes, indicating the distributions of story torques along the height are similar both in the static and dynamic procedure of calculation for the configuration of the structure under study. They differ in the magnitude predicted, with the normalized dynamic torques having the largest value while the NBC 77 static torque having the smallest value. Since the torque envelopes are similar in shape, the base torque values would be a good indicator on the relative magnitude of the different torque envelopes.

Shown in Fig. (4) are the variations of the normalized dynamic torques as a function of the uncoupled periods ratio τ. The modal contributions are combined in two ways. In the first instance, they were combined according to the root sum square(RSS)rule. This curve shows that there is a dramatic increase of torques as the uncoupled period ratio approaches unity, caused by the effect of sympathetic coupled torsional lateral resonance. However, for the sympathetic coupled resonance to occur, it is necessary that some of the actual torsional predominant periods and corresponding lateral predominant periods be close to each other. Therefore, the RSS rule of combining the modal responses should be modified to account for the closeness of vibrational periods of different modes. One such rule taking into account the closeness of modal periods is given by Newmark and Rosenbleuth [11]

$$Q^2 = \sum_n Q_n^2 + \sum_{\substack{n\ m \\ m \neq n}}\sum \frac{Q_m Q_n}{1+\varepsilon_{mn}^2} \qquad (5)$$

where

$$\varepsilon_{mn} = \frac{\sqrt{1-\delta^2}}{\delta}\,\frac{\omega_n-\omega_m}{\omega_n+\omega_m}\,, \qquad (6)$$

and Q_m is the mth modal response, ω_m is the frequency of the mth mode and δ is the damping value, assumed to be a constant in this analysis. Interpretating eqn. (5) for the case of story torque calculation, the total torque is given by

$$(M_t)^2 = \sum_n (M_t)_n^2 - \underset{m \neq n}{\sum_m \sum_n} \frac{(M_t)_m (M_t)_n}{1 + \varepsilon_{mn}^2} \qquad (7)$$

where $(M_t)_n$ is the torque due to mode n.

The normalized dynamic base torque based on this combination rule is also shown in Fig. (4). It is seen that the sympathetic coupled resonance effect is substantially reduced due to cross modal torque interference.

Shown in the same graph are base torque values computed using five representative seismic codes. Similar plots of torque envelopes and base torque values are presented in Fig. (5 and 6) for the case of moderate eccentricity (e = 10%D). A number of observations can be made based on the data presented.

First of all, it is believed that the dynamic torque values obtained based on eqn. (7) is the "best" estimate of torque values, within the framework of response spectrum technique. Comparing the dynamic torque curves based on the root sum square rule, it is seen that the RSS rule to combine modal torque contributions grossly overestimates the torque at $\tau = 1$ in the case of small eccentricity, and somewhat overestimates the torque values in the case of moderate eccentricity. In the former case, the overestimate is by a factor of two and in the latter case, the overestimate is about 16%. In both cases, the RSS curve and the curve based on eqn. (7) give essentially the same value when the uncoupled torsional period is not within 25% of the uncoupled lateral period, i.e. $\tau < 0.75$ or $\tau > 1.25$. This indicates that the coupled periods of the torsional predominant and lateral predominant modes are sufficiently well separated in these ranges that the cross modal torque interference is indeed small. The difference in the amount of overestimation at $\tau = 1$ can also be understood in terms of cross modal torque interference. For small eccentricity, the coupled periods of the first two modes are only marginally separated. The torsional responses for the first mode is almost out of phase with the torsional response of the second mode so that the cross modal torque interference is very large. As a result, the difference between the RSS estimate and that of eqn. (7) is large. At larger eccentricity, the coupled periods are separated further apart so that the phase of the torsional responses of the pairwise coupled modes are further detuned, resulting in less cross modal interference.

In comparing the base torque according to NBC 77 and the maximum value of normalized dynamic base torque calculated according to eqn. (7), it is noted that the NBC 77 value underestimated the dynamic torque at $\tau = 1$ by a factor of two. In the cases of small and moderate eccentricity studied, NBC 77 gives 61% and 55% respectively of the dynamic torque value at $\tau = 1$. When the uncoupled period ratios are ± 25% away from unity, NBC 77 provides a good estimate of the dynamic torque value. In this respect, one may conclude that when the uncoupled torsional and lateral periods are separated by twenty-five percent, the effect of sympathetic coupled resonance may be neglected.

For building code consideration, it is necessary to evaluate how common it is that buildings have torsional and lateral periods that are close to one another. Since accurate methods of torsional period estimation for real buildings are still quite primitive, the best source of information comes from the testing of actual structures. Hart et al. [12] studied the ambient building periods for ten steel buildings and nine reinforced concrete buildings in the Los Angeles area in California. This group of buildings range from 7 to 52 stories, and lateral periods from 0.57 seconds to 5.46 seconds. Out of these 19 buildings studied, 10 of them have their fundamental torsional periods within 25% of the lateral periods. It should be noted that the reported test periods are coupled vibrating periods which are separated further apart than uncoupled periods. If the uncoupled periods were worked out, one can speculate that more than 10 buildings out of the 19 buildings tested would have values of τ which are within 25% of unity. Based on this study, it would appear that it is not uncommon to have buildings in which the effect of sympathetic resonance becomes significant and should be allowed for in the code.

Currently, the format in NBC 77 is to warn the designer of the existence of such a phenomenon and refer to Commentary K for further information. Meanwhile, the code formula provides no allowance for such effect. Since there is no necessity to calculate the torsional periods in the static code procedure, it is unlikely that an average designer will calculate the torsional period, estimate the torsional-lateral period ratio to realize the necessity of including the sympathetic resonance effect in the design. A better code format would be to increase the torsional moments required from the current requirement so that the effect of sympathetic resonance is taken into account automatically. The specified required torsional moment can then be reduced if the designer can show that the sympathetic resonance effect will not be significant in the design. Under this new format, an incentive is provided for the designer to calculate the torsional period and the uncoupled period ratio.

Of the five seismic codes shown, it appears that only the German code provides a good estimate of the dynamic torque. In the German code, an additional term in the design eccentricity expression is added to include the sympathetic coupled resonance effect [8]. The remaining four seismic codes have no provision for this effect, although the sympathetic coupled resonance effect was recognized. Their ability to approximate the dynamic torque at sympathetic resonance essentially depends on the conservatism on torsional effect of each code. In a decreasing order, they are the New Zealand code, Mexican code, Canadian code and the U.S. code.

The results for the case of exceptionally large eccentricity ($e = 50\%D$) is shown in Fig. (7). Since the design eccentricity is larger than 25% of plan dimension, NBC 77 requires the static torque used in design be doubled to that calculated using the NBC 77 static formula. The resulting torque envelope is shown by the curve marked NBC 77. As a comparison, a curve marked 1/2 NBC 77 is also presented to provide a comparison to show if the requirement of doubling the torque is ignored. Shown also in the figure is the normalized dynamic torque curve. It can be seen that even without doubling the result calculated by using the NBC design eccentricity formula, the static torque curve has conservatively enveloped the dynamic torque curve. Therefore, doubling the computed static torque as currently specified in NBC is a very conservative requirement for buildings with large eccentricity.

As pointed out in earlier sections, the ratio of uncoupled periods close to unity does not imply closeness of the coupled periods for large eccentricity. As an example, the dynamic curve presented is for the case when $\tau = 1$. Due to the large eccentricity in this case, the actual fundamental periods for the first two modes are 1.33 sec. and 0.47 sec. respectively.

DESIGN TORQUE ON BUILDINGS WITH ECCENTRICAL OFFSET

Due to the sunlight exposure laws in cities, many buildings have to be designed with some degree of eccentric offset at the upper part of the building as shown in Fig. (8). In the NBC 77 code, the structural eccentricity value is a local measure of the floor configuration and the effect of eccentric offest is not taken into account. A modification on the definition of structural eccentricity e is proposed for NBC 79. For floor x, e is given by

$$e = \frac{\sum_{i=x}^{N} F_i e_{ix}}{\sum_{i=x}^{N} F_i} \qquad (8)$$

where e_{ix} = distance between the center of mass at floor i to the center of resistance at floor x; and N is the total number of floors. The formula given in eqn. (8) essentially provides an equivalent structural eccentricity for floor x by considering all the torques caused by forces above and including floor x. In this respect, the effect of eccentric offset of the upper stories has been taken into consideration. It can easily be verified that when a building has the centers of mass and also the centers of resistances of the floor lie on top of one another, eqn.(8) gives a value of structural eccentricity identical to the former definition of structural eccentricity.

To study the applicability of the new formula, a series of three structures with eccentric offset are considered. These structures are derived from the twelve story structure investigated in the previous section. It is assumed in the first structure that the top two stories are eccentrically offset. The other two structures have top four, and top six stories offset eccentrically as shown in Fig. (8). The interstory lateral stiffness and the mass of each offset floor are taken to be half of those in the regular floors. The torsional stiffness and the polar moment of inertia about the mass center of each offset floor one taken to be 31% that of those in the regular floors below. The value of 31% is arrived at by assuming the columns in the exampled buildings are regularly spaced. It is assumed that for each floor, the mass center coincides with the center of resistance so that there is zero structural eccentricity for every floor as defined by NBC 77. The eccentricity of the building is entirely due to the eccentric offset.

The story torque comparison for these three buildings are shown in Figs. (9, 10, and 11). Three torque curves are shown in each figure, corresponding to calculations based on the NBC 77, on the proposed formula to appear in NBC 79, and finally based on dynamic response spectrum analysis. The torque values based on dynamic analysis presented at the offset floors are adjusted such that at each offset floor the loading consists of a torque with the value as shown acting at the center of resistance of the floor together with a shear force acting through the same point.

The torque diagrams at the offset floors are the same for both the NBC 77 and NBC 79 calculations. However, there is a substantial difference at floors below the offset of the building. The NBC 77 curve is computed using the design eccentricity equal to 5% of the floor dimension while the NBC 79 curve is calculated based on a modification of structural eccentricity e as given in eqn. (8). The dynamic torque envelope is the result of the RSS combination of twelve modal responses.

It can be seen that both the NBC 77 and NBC 79 curves underestimates the story torques at the offset floors. In the building with six floors offset, the torque at the base of the offset portion of the building is more than seven times that predicted by the code formulae. At floors below the offset, the NBC 77 curve underestimates while the NBC 79 overestimates the dynamic torque. It should be noted that in computing the NBC 79 curve, the requirement of doubling the torsional moment in the cases when the design eccentricity exceeds 25% of the plan dimension has been neglected. If this requirement were observed, the NBC 79 curves will show an even larger overestimation of the dynamic curve.

The dynamic torque curves for the three buildings are replotted in Fig. (12). It is interesting to note that not only the magnitude of the story torque increases as the number of offset floors increase, but also the shapes of the curves change due to the change of mode shapes in the buildings. In the building with a six offset floors, the dynamic torque at the base of the offset is larger than the torque experienced by the floor below it. No static code formula is likely to be able to simulate such a distribution of torque. The relatively large torque at the bottom of the offset stories can have considerable design implication since the torsional stiffness of the offset stories are smaller than the lower part of the building. Therefore, one can expect substantial torsional shears on the columns at the bottom of the eccentric offset.

CONCLUSION

Based on the current investigation, the following tentative conclusions can be drawn.

1. The NBC 77 static torque format, involving the product of story shear and design eccentricity, provides adequate description of the distribution of story torques along the height of the building, provided the mass centers, and the centers of resistance of the floors lie on two vertical axes, and also the effect of sympathetic coupled resonance can be neglected.

2. Sympathetic coupled resonance of torsional and lateral vibration is significant only if the buildings have small eccentricity, and the uncoupled torsional and lateral periods are close to each other. The effect of sympathetic resonance can be neglected if the uncoupled torsional period is not within 25% of the fundamental lateral period.

3. If the effect of sympathetic coupled resonance is significant, one of the three following approaches can be taken:

   a) the static torque as computed according to NBC 77 should be doubled.

   b) an additional factor be included in the design eccentricity expression to allow for this effect. The expression as given by Muller and Keintzel appears to be a viable correction to take into account of the sympathetic coupled resonance effect.

   c) a dynamic approach can be used, using the response spectrum technique. It should be noted that a root sum square combination of the modal torque contribution will overestimate the torque values. The modal contributions should be combined by more refined rules such as given in eqn. (7) which takes into account the modal torque interference.

4. For buildings with large eccentricities, the static torque as computed by NBC code formulae adequately estimate the story torque. Doubling the computed static torque as currently specified in NBC 77 is a very conservative requirement.

5. While the modification of the calculation of eccentricity e in NBC 79 gives the impression that it is applicable to buildings with eccentric offests, its use to such buildings should be carried out with caution. The new formula leads to conservative estimates on the main portion of the building, but it still has the same drawback as the NBC 77 code in that the torques at the offset portion of the building are grossly underestimated. So the improvement is only partial. Buildings with eccentric offsets are irregular buildings and only a dynamic approach such as the response spectrum technique can lead to a realistic estimate of the torque distribution. Codes should state explicitly that the static approach is only applicable to buildings whose centers of mass and centers of resistance lie in two vertical lines. A dynamic analysis is necessary if the structure does not satisfy such stated conditions.

ACKNOWLEDGMENT

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TABLE 1

Country	Design Eccentricity	Comment
Canada [1]	$e_x = 1.5e + 0.05D$ or $e_x = 0.5e - 0.05D$	Torsional shear on member based on worse of two cases
Germany [2]	$e_x = e + e_1 + 0.05D$ or $e_x = e - 0.05D$	Torsional shear on member based on worse of two cases
Mexico [3]	$e_x = 1.5e + 0.10D$ or $e_x = e - 0.10D$	Torsional shear on member based on worse of two cases
New Zealand [4]	$e_x = 1.7e - e^2/D + 0.10D$ or $e_x = e - 0.10D$	Torsional shear on member based on worse of two cases
Turkey [5]	$e_x = e + 0.05D$	--
U.S.A. [6]	$e_x = e + 0.05D$	Negative torsional shear on member neglected
U.S.A. (ATC 3-06)[7]	$e_x = e + 0.05D$ or $e_x = e - 0.05D$	Torsional shear on member based on worse of two cases

e = structural eccentricity

e_1 = eccentricity factor to allow for sympathetic resonance effect [8]

D = plan dimension of floor

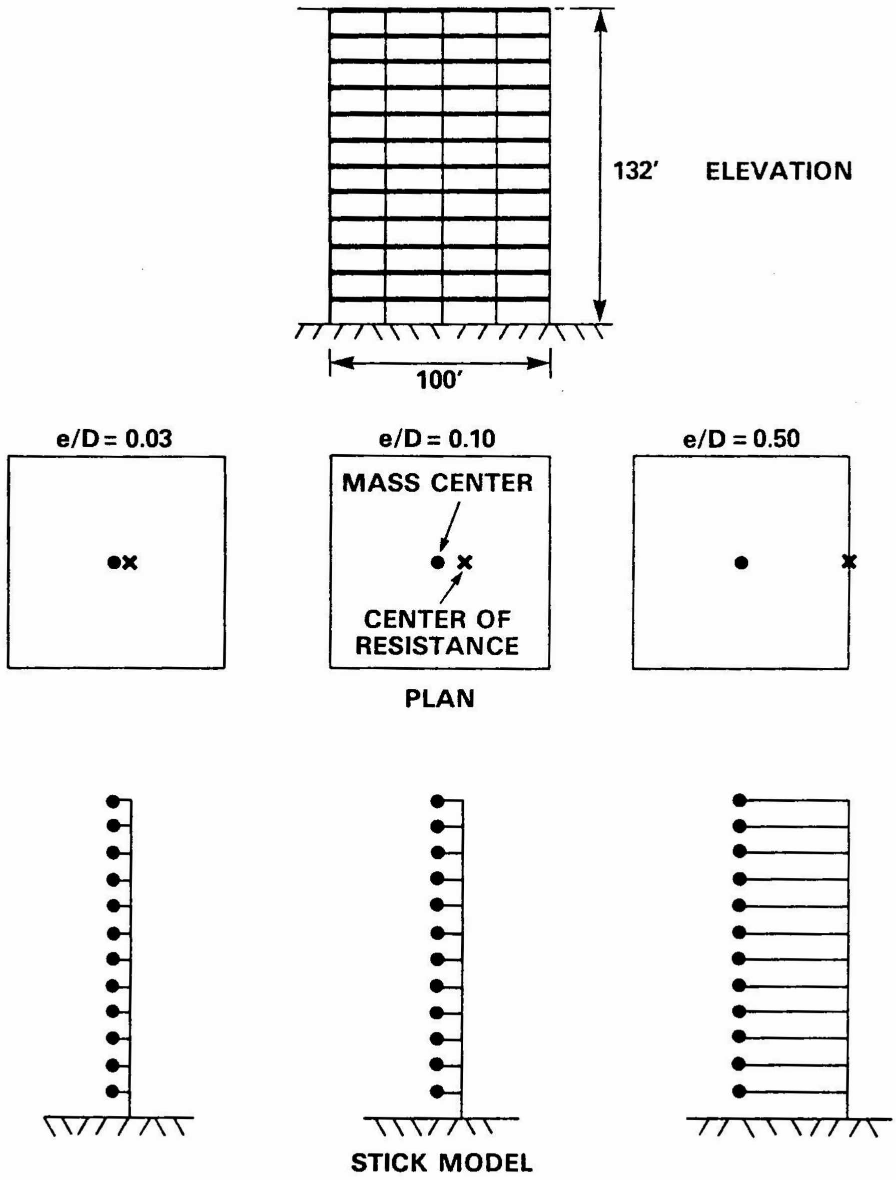


FIG. 1 MATHEMATICAL MODEL FOR MONOSYMMETRIC BUILDINGS

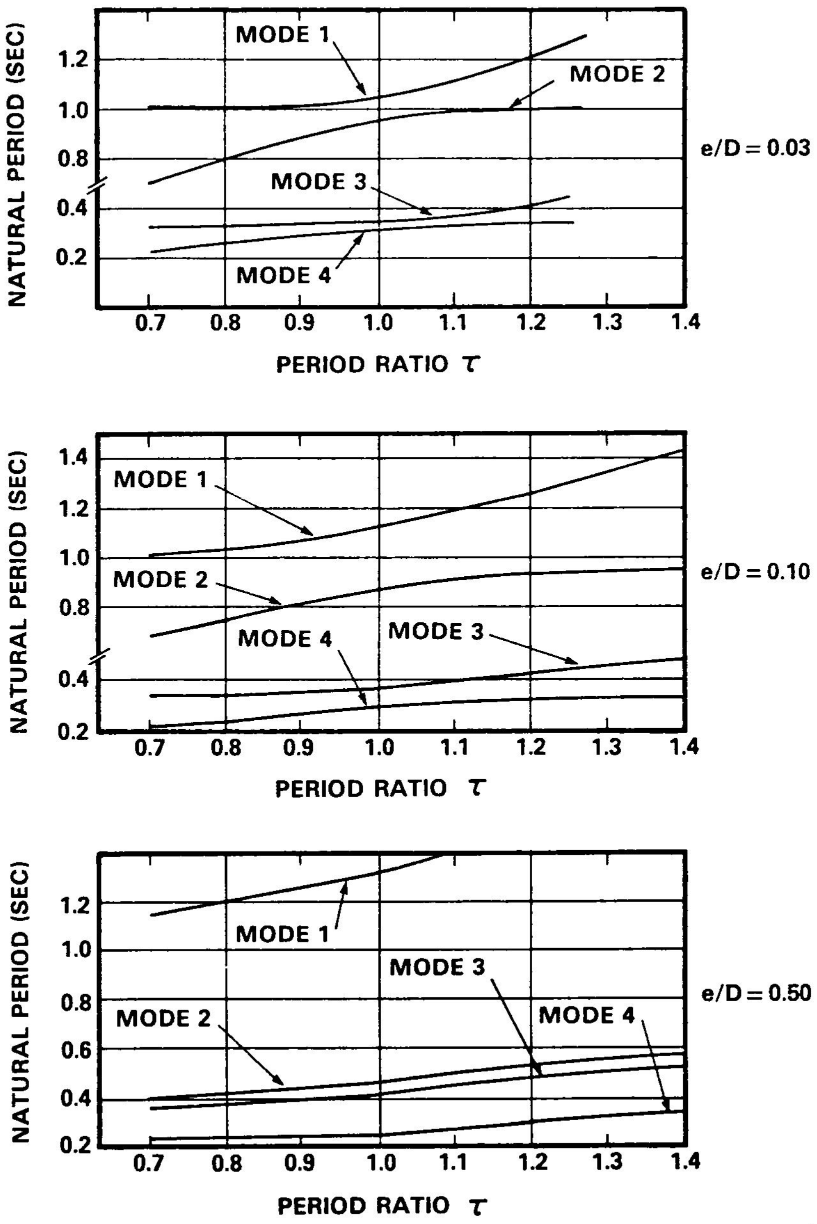


FIG. 2 EFFECT OF ECCENTRICITY AND UNCOUPLED PERIODS RATIOS TO NATURAL PERIODS OF BUILDING (T_x = 1.00 SEC)

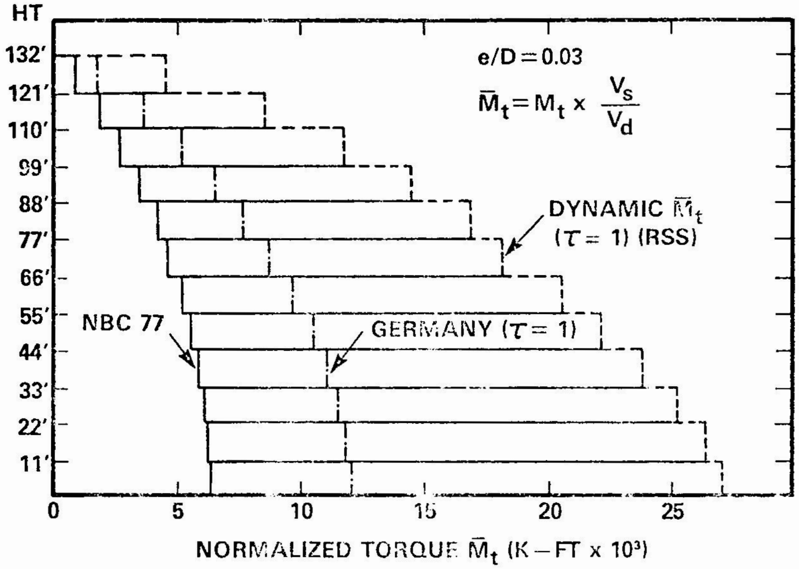


FIG. 3 COMPARISON OF TORQUE FOR BLDG. T_x = 1.0 SEC

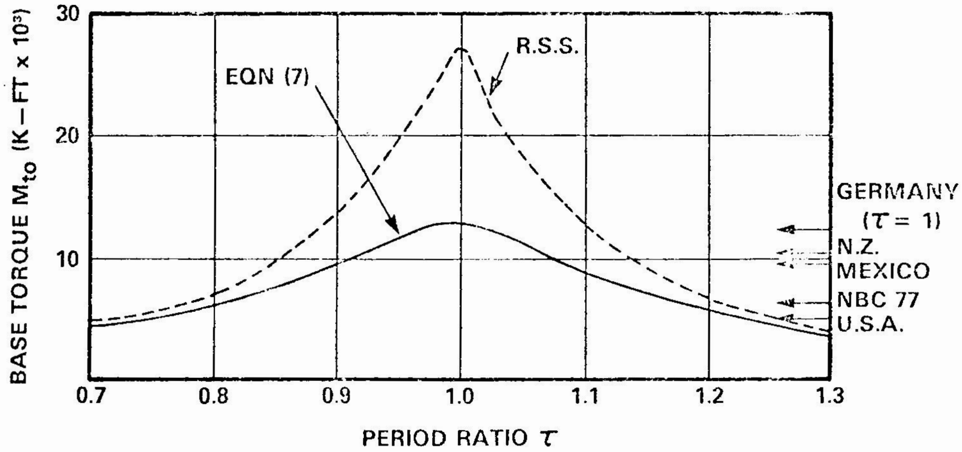


FIG. 4 THE EFFECT OF TORSIONAL PERIOD FOR BLDG.

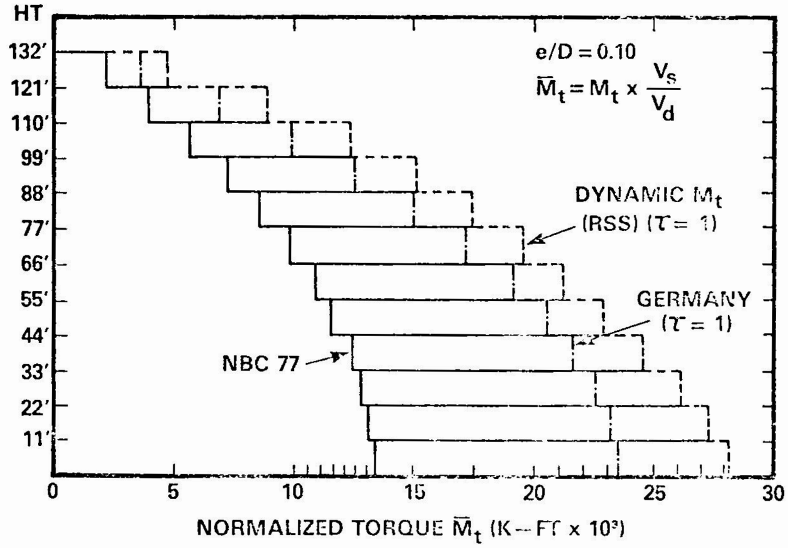


FIG. 5 COMPARISON OF TORQUE FOR BLDG. $T_x = 1.00$ SEC

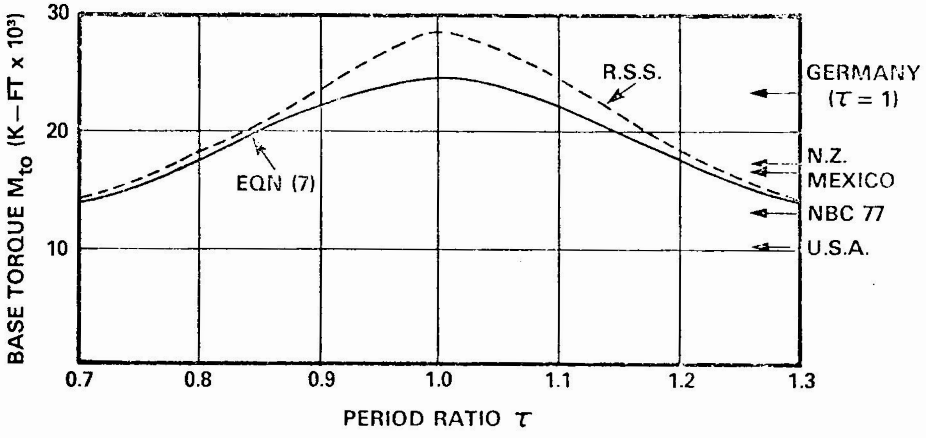


FIG. 6 THE EFFECT OF TORSIONAL PERIOD FOR BLDG. $T_x = 1.00$ SEC

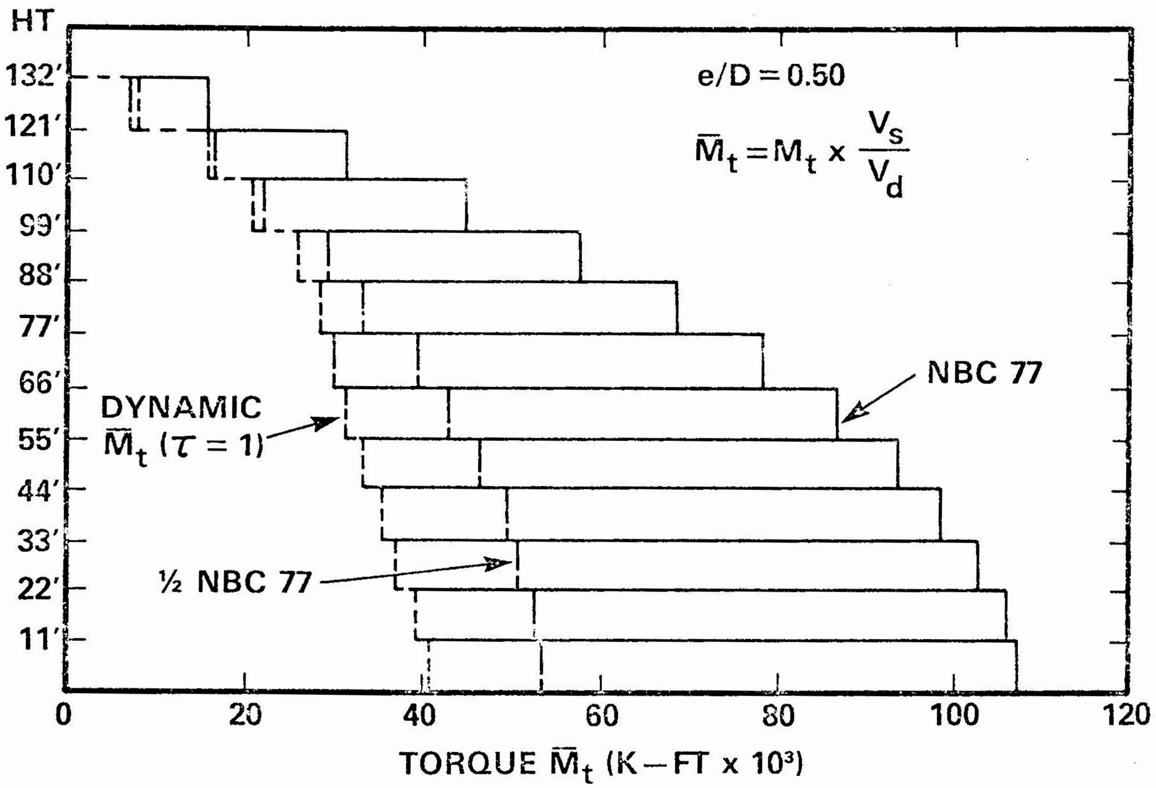
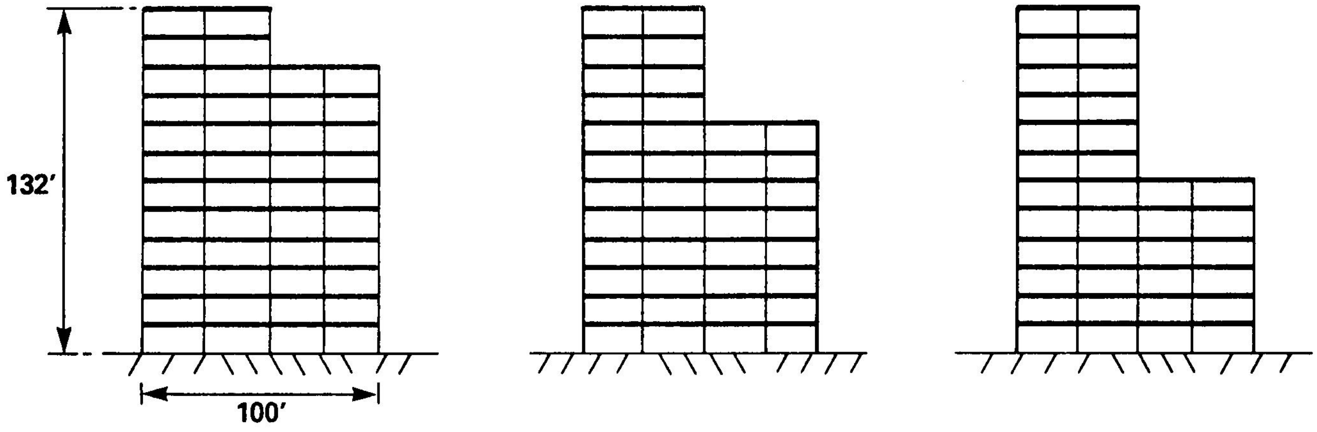


FIG. 7 COMPARISON OF TORQUE FOR BLDG. WITH LARGE ECCENTRICITY



STRUCTURE A

STRUCTURE B

STRUCTURE C

FIG. 8 BUILDINGS WITH ECCENTRIC OFFSET

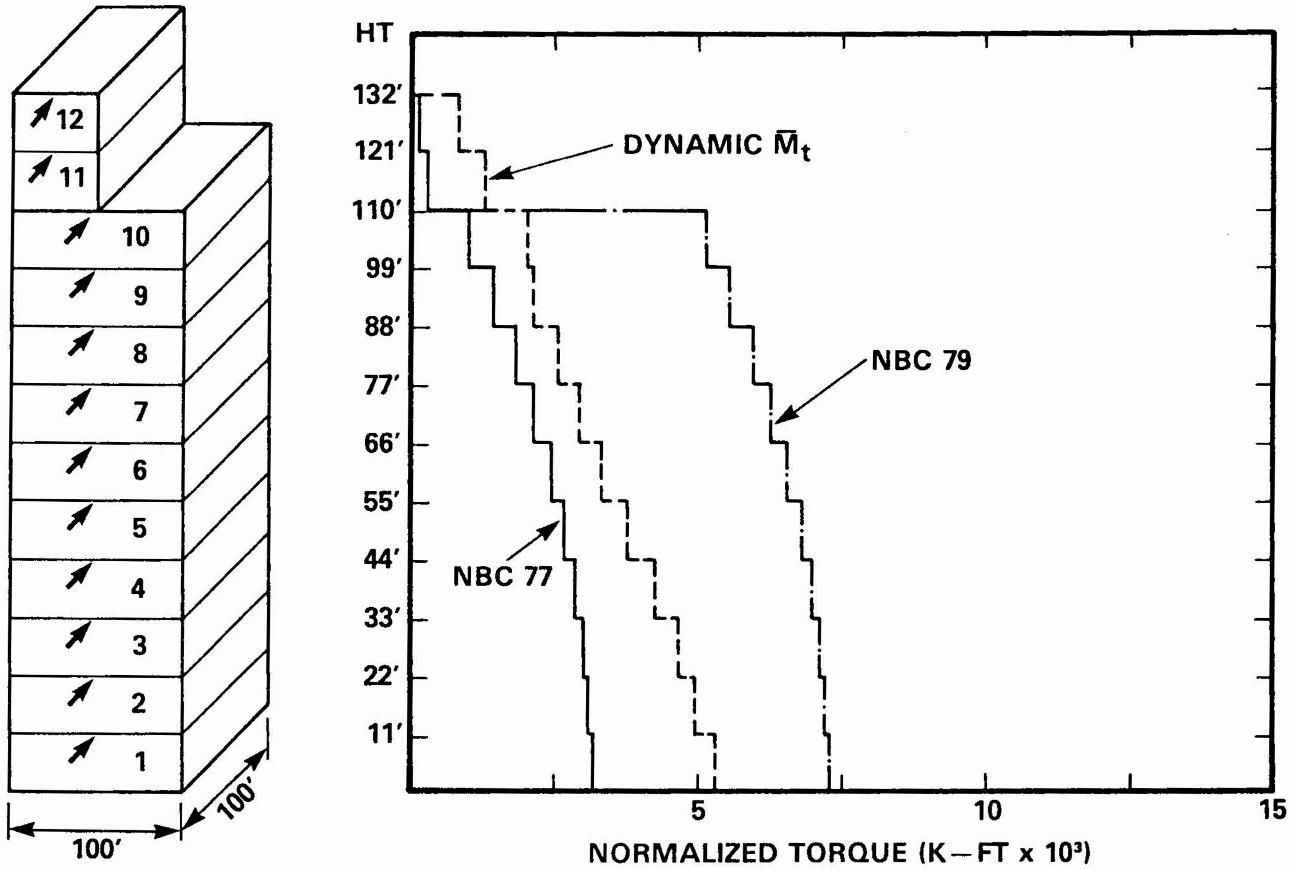


FIG. 9 TORQUE ENVELOPE FOR STRUCTURE A

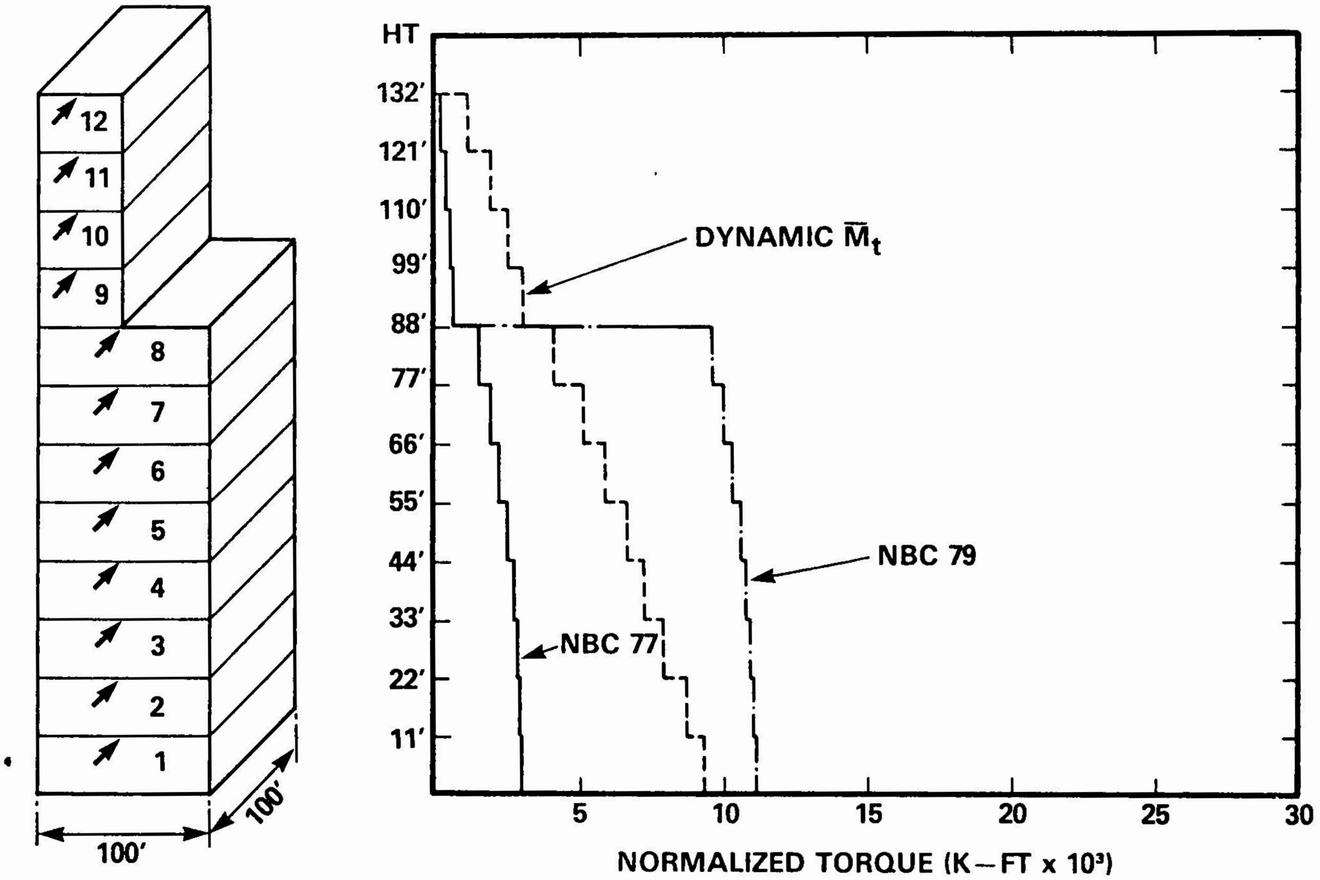


FIG. 10 TORQUE ENVELOPE FOR STRUCTURE B

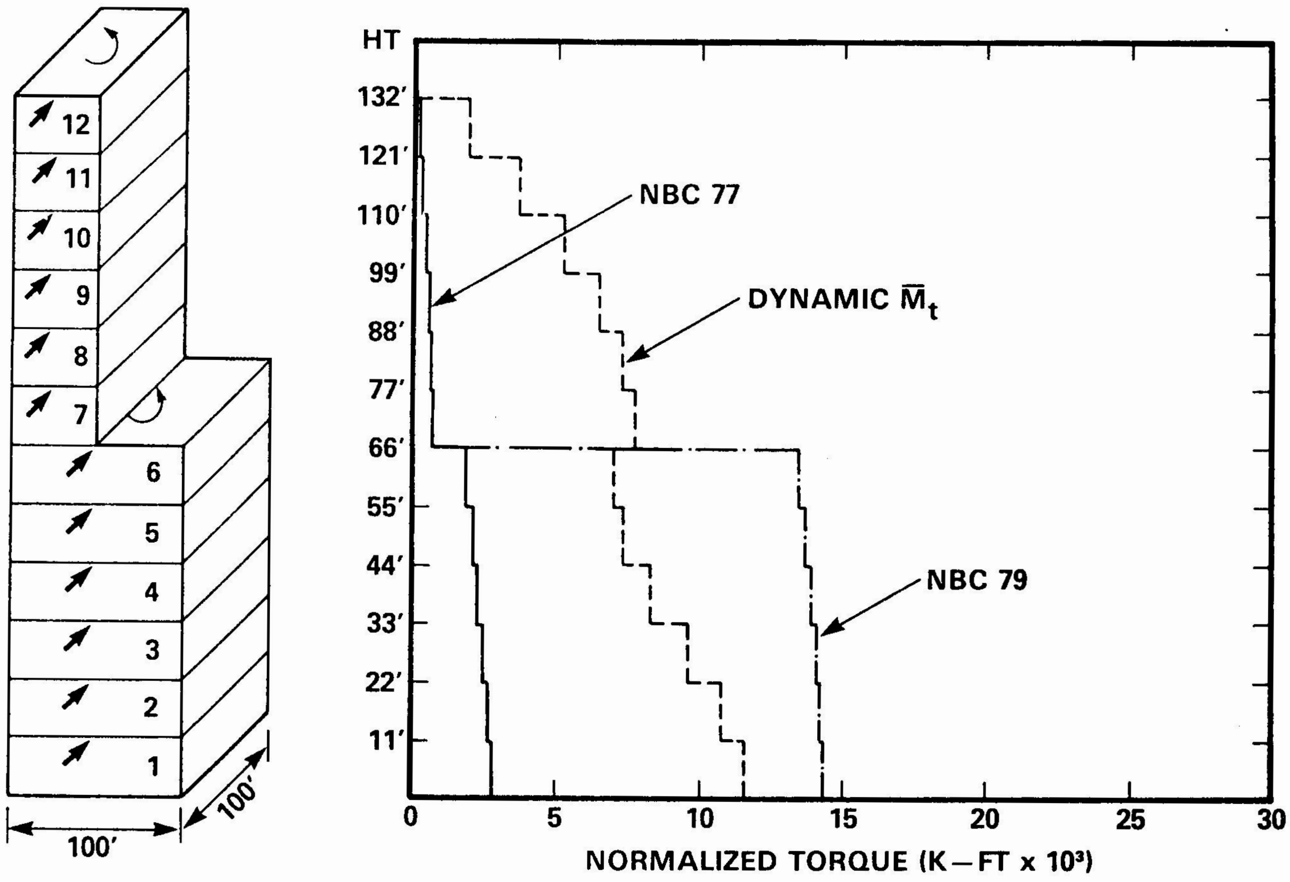


FIG. 11 TORQUE ENVELOPE FOR STRUCTURE C

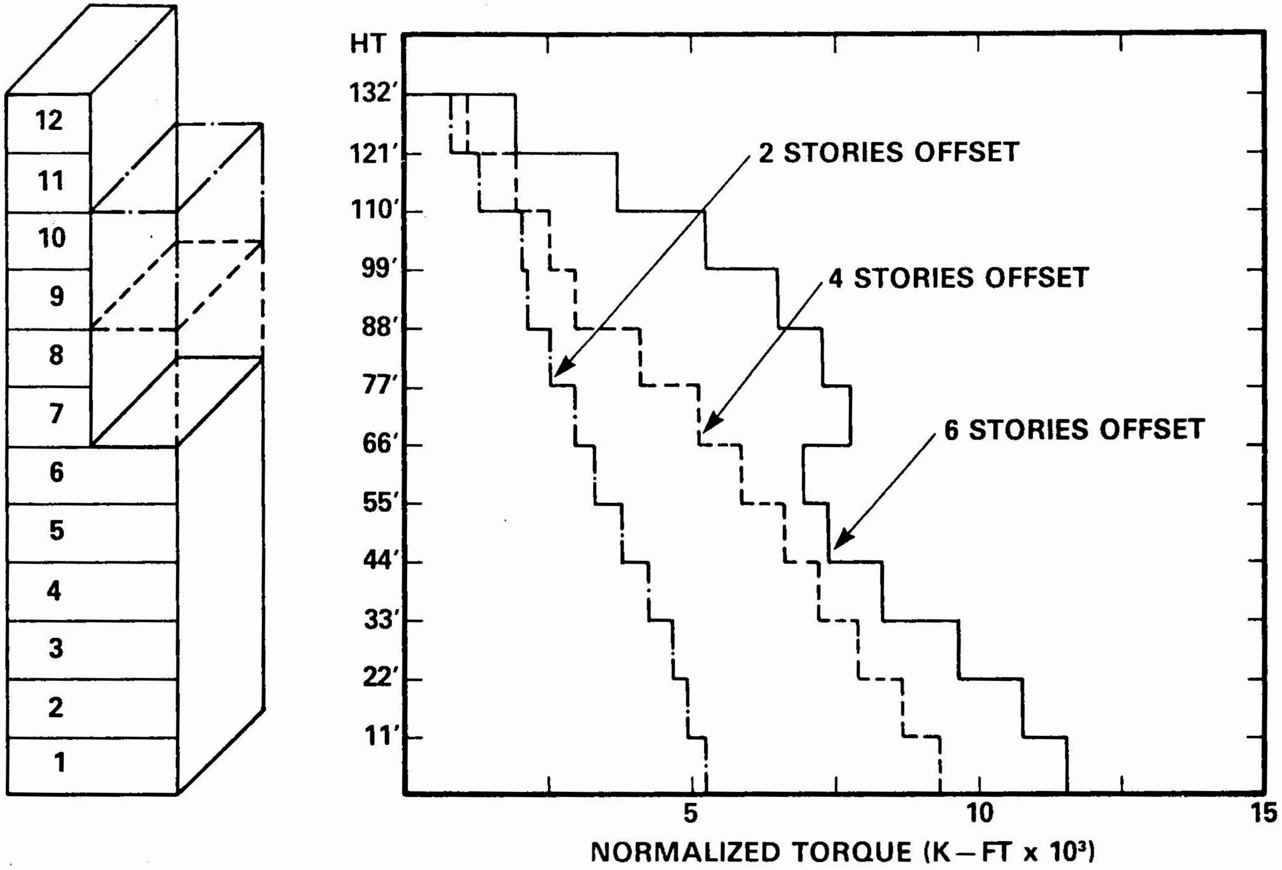


FIG. 12 COMPARISON OF DYNAMIC TORQUES FOR OFFSET STRUCTURES