DYNAMIC RESPONSE OF INELASTIC BUILDING-FOUNDATION SYSTEMS

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ABSTRACT

This paper examines the importance of two-dimensional soil-structure interaction (SSI) on the dynamic response of inelastic building-foundation systems located on sites where SSI effects can be significant. The building is modeled as an elastic-plastic one-story structure, meant to represent the first translational modal response of actual buildings, resting on an embedded foundation. A parametric study is conducted to assess the effects of the various SSI parameters on the steady state seismic response. The focus of the study is on the ductility demands, inter-story drifts, inelastic dissipated energy, and total lateral displacements.

The results show that SSI leads to significant changes in the dynamic response of SSI systems as compared to the associated fixed-base systems. Moreover, for inelastic systems it is observed that the peak value of the response, including SSI effects, can be greater than that for the corresponding fixed-base systems. Thus, contrary to current seismic provisions, neglecting SSI effects can lead to non-conservative results. This finding points to the need of incorporating SSI in the dynamic analysis to avoid inaccurate evaluation of the seismic response. Special attention should be paid to properly estimating the SSI parameters including factors such as layering, proximity to other structures, stiffness of the foundation members, and embedment.

INTRODUCTION

The seismic design of buildings, according to current building codes, is based on static or dynamic analyses that consider elastic behavior. Effects of inelastic behavior during strong earthquakes are taken into consideration by reducing by a global factor the forces obtained in the elastic analysis. Such a factor is derived from comparisons of the response of simple elastic and inelastic models, and is justified in practice on the basis of the overall performance of different types of buildings during actual earthquakes. Therefore, while elastic analysis remains the most widely followed approach for the seismic design of building, an assessment of the inelastic response is necessary to ensure proper performance under severe events.

The objective of this study is to evaluate the impact of two-dimensional soil-structure interaction (SSI) on the inelastic response of building-foundation systems under seismic excitation. In pursuing this objective, we have conducted a parametric analysis of a single-story model using two prototype foundation conditions: one very stiff (fixed base) and the other simulating soft soil conditions. We focus our attention on the response quantities that are most important in seismic design of buildings, namely ductility demands, interstory drifts and total lateral displacements.

FORMULATION

The soil structure interaction (SSI) system under investigation is presented in Figure 1. It comprises an inelastic single-degree-of-freedom structure with mass m_1, initial period T_1 and 5.0 percent fixed-base damping ratio, intended to represent the first translational fundamental mode of a multistory building. This structure rests on a rigid foundation with mass m_0, embedded in an elastic flexible soil, and with no slippage allowed between the base and the soil. The soil flexibility allows horizontal translation and rocking at the structure's base yielding a system with three degrees of freedom. The SSI horizontal and rocking stiffness coefficients and the corresponding SSI damping ratios are derived from recommendations by Gazetas (1991) and NEHRP (1997). In fact, in this study, we regard as the primary SSI parameter the ratio $\lambda = T_1'/T_1$ of the modified SSI period to the fixed-based period of the structure. A second parameter is the slenderness ratio H/B of the structure, where H is the height and B the side dimension of the base. From these parameters we back-calculate the corresponding horizontal and rocking stiffness coefficients. To define the SSI parameters we have considered that the number of stories of the modeled building is 10 T_1, with a height of 3.0 meters per story, yielding a structure height, H, equal to 30 T_1, in meters. The effective height of the single-degree-of-freedom model has been taken as $h_1 = 0.7H$. The floor and the foundation mat of the model are both taken to be square, with side dimension B and rocking radius of gyration $B/\sqrt{12}$. The embedment depth of the foundation is taken to be equal to 0.2 H and the base mass, $m_0 = 0.2\ m_1$. The seismic input motion is a vertically incident SH-wave, neglecting the kinematic interaction of the foundation. In the time variable it is taken to be harmonic with unit amplitude and period T_0.

We have considered two types of systems. First, a fixed-base structure, with T_1 varying from 0.4s to 4.0s. Then, for each value of T_1, we consider two associated SSI systems, such that $\lambda = 1.2$ and $\lambda = 1.4$, respectively. The three equations of motion of the SSI system were derived by standard procedures (see, e.g., Jennings and Bielak, 1973, and Bielak, 1978) and solved by numerical integration using an implicit Newmark step-by-step procedure. A sufficiently high number of excitation cycles were used to reach steady-state response. All the results presented in the next section correspond to a slenderness ration H/B = 4. Results for H/B = 2, not shown here, are similar. This means that the main effect of H/B is in the way in which affects λ.

PARAMETRIC STUDY RESULTS

Figure 2 shows the inter-story drift of the single-degree-of-freedom structure, in meters, as a function of the period ratio T_1/T_0. There is no need to define ductility ratio for elastic systems; the dynamic analysis provides the maximum elastic force in the structure. For each value of T_1/T_0, the yield forces of the inelastic systems were selected as a fraction of the maximum elastic force in order to attain prescribed values of the ductility demand ratio, μ. This is the ratio of the maximum relative displacement of the mass m_1 with respect to the base to the yield displacement. Three values of μ are depicted in Figure 2. This figure shows the well-known result that for elastic structures the peak response generally decreases with increasing flexibility of the foundation. On the other hand, the opposite is true for the inelastic structures. This behavior had previously been observed by Bielak (1978). It is important to emphasize that for the fixed-base structure (λ = 1) the response of the inelastic structure is drastically different from that of the elastic one. For increasing values of λ (i.e., increasingly softer soil), the peak value of the response increases. While the resonant frequency decreases with λ, the change is less pronounced than for the elastic systems. Actually, the greatest reduction in the resonant frequency is due to the softening effect of the inelastic response, even for the smaller value of the ductility ratio.

Dynamic amplifications factors with respect to the static inter-story drift are presented in Figure 3 for ductility ratios of 2 and 4. It can be observed that for a prescribed ductility ratio, the amplification factor decreases with increasing soil-structure interaction (increasing T_1'/T_1) for relatively low T_1/T_0 ratios. When T_1/T_0 increases, this trend reverses: the lesser the interaction, the smaller the amplification factor. The transition T_1/T_0 ratio is about 0.7 for ductility demand of 2, and approximately 0.65 for ductility demand of 4.

Figure 4 depicts the reduction factors that need to be applied to the maximum elastic force in the structure in order to achieve a ductility demand of 4. Two approaches were used to calculate the maximum elastic force. In the first approach, the reference elastic analysis was performed considering SSI. In the second approach, the elastic analysis assumes that the structure is fixed-based. In all cases, the inelastic response is calculated including SSI.

In separate analyses, the yield forces of the structures were determined such that the ductility demand adopts a prescribed value (2 or 4) for the fixed base case. This simulates the common practice in which the structure is designed ignoring SSI. The fixed-base yield forces were then incorporated into the SSI systems and the corresponding SSI analyses were conducted. The resulting ductility demands are presented in Figure 5. For the fixed-base systems (λ = 1), the ductility demands are 2 and 4, respectively, independently of T_1/T_0, in agreement with the criterion used for selecting the yield forces. On the other hand, the ductility demands depart significantly from the target value when SSI is accounted for: higher demands result for T_1/T_0 smaller than approximately 0.7, and the opposite occurs for T_1/T_0 beyond this value. These effects are more noticeable for λ = 1.4 than for λ = 1.2, i.e., when the interaction is more significant.

The total displacement, u_{tot}, of the mass m_1 with respect to the ground is the sum of its relative displacement with respect to the base, u, the base displacement and the product of the base rotation by h_1. Figure 6 shows the ratio u_{tot}/u for the inelastic systems divided by the same ratio for the associated elastic system. The results exhibit a very small variation with T_1/T_0. By definition, 100 percent correspond to the cases of elastic interaction. Practically constant values of approximately 80 percent for λ = 1.2, and 65 percent for λ = 1.4 were obtained. The analyses were repeated for the SSI systems calculating the structure yield forces using the fixed-base system. Only small differences with respect to the previous results occur with this criterion.

We have also calculated the hysteretic energy in the structure per cycle of vibration. The energy dissipated in the viscous damper of the structure was not included in this calculation. The results, normalized by the weight of the structure, m_1g, are depicted in Figure 7. The normalized values can be physically interpreted as the distance by which the structure could be lifted above the ground using the dissipated energy. The results for the three levels of interaction considered herein are only slightly distinguishable for T_1/T_0 greater than 0.6. In all cases, the normalized dissipated energy is approximately 0.17 meters at T_1/T_0= 0.6, and decreases sharply for larger values of this ratio. For smaller values of T_1/T_0, the dissipated energy increases with the extent of SSI (i.e. with larger values of λ). This increase is much more noticeable when the yield level has been defined ignoring the SSI.

STUDY OF THE PARQUE ESPAÑA BUILDING IN MEXICO CITY

In this section we examine the behavior of an actual building (Parque España) on a pile foundation located in the lakebed region in Mexico City. This building experienced essentially no damage during the 1985 Mexico earthquake. It had been retrofitted following an earlier earthquake, which had caused significant damage to it. Forced vibration tests were conducted after the 1985 earthquake to determine its condition, dynamic properties, and SSI effects (Foutch et al, 1989). SSI periods, damping, and displacements under small vibrations were determined as part of the study. Figure 8 shows a profile of the Parque España building, together with the fundamental mode shape, natural period, and damping ratio of the SSI system in the NS direction. This model is used in our study to examine inelastic effects of the structural response. Based on the observed parameters, the fixed-base natural period of the structure is calculated to be 0.85 s, and the measured value of the ratio $\lambda = T_1'/T_1 = 1.23$. The yield force of the structure is chosen such that the maximum ductility demand of the fixed-base structure at resonance will attain a prescribed value. Here we selected the cases $\mu = 2$ and $\mu = 4$. Figure 9 shows the frequency response of the ductility demand for the fixed-based structures for the two values of μ, and for the corresponding SSI systems, which include the pile foundation. It is noteworthy that the peak values of the SSI systems are greater than those for the corresponding fixed-based systems. Also, for periods of excitation T_0 less than $1.3T_1$ for the yield force F_y corresponding to $\mu = 2$, the ductility demand of the fixed-based system exceeds that of the SSI system. For greater values, the reverse is true. Similar behavior is observed for the more ductile system corresponding to $\mu = 4$.

The maximum interstory drift, u, is shown in Fig.10 as a function of the normalized period of excitation, both for the elastic and the inelastic structures. There is a large reduction in the peak values of the response of the fixed-based structure due to inelastic action, and a further reduction through the combined SSI and inelastic effects. The peak values of the response for the inelastic systems with SSI, however, are greater than that for the corresponding fixed-based systems.

The last two figures clearly indicate that SSI effects are not always beneficial. This behavior is reaffirmed in Figure 11, which shows the hysteretic energy per cycle for the inelastic systems. The peak values of this energy for the SSI system also exceed those for the corresponding systems in which SSI effects are neglected. The hysteretic energy in the SSI system is greater than that corresponding to the fixed-based system for higher periods of excitation, T_0, and changes direction for decreasing values of this parameter.

CONCLUSIONS

The analyses presented in this paper show that the dynamic response of a building-foundation system including soil structure interaction can be significantly different from that calculated with a fixed-base model. Simple single-story models have been used for rapid evaluation of SSI effects under steady-state excitation. The results show very appreciable changes in dynamic amplification factors of the static response, in ductility demands, and in relative and total displacements of the structure. These SSI effects are mainly the result of the increase in the fundamental period, and are much more pronounced when the inelastic behavior of the structure is neglected in the dynamic analyses.

For the fixed-base systems examined in this paper, in general, beneficial effects of SSI occur for ratios T_1/T_0 (structure fundamental period to the excitation period) larger than approximately 0.7. Conversely, below this limit the SSI benefits quickly diminish as T_1/T_0 decreases, and the effects become detrimental. Our results also indicate that the inelastic structural behavior in SSI systems changes significantly the seismic response parameters as compared to the elastic analyses response. Inelastic behavior smoothens significantly the typically sharp peaks of elastic spectra. This results from energy being dissipated mainly through hysteretic loops in the structure. This suggests that SSI inelastic analyses should be the basis for evaluating Code reduction factors of the elastic design coefficients and amplification factors in order to estimate inelastic lateral displacements produced by elastic analyses.

As a rule, better correlations between inelastic and elastic responses are achieved when the elastic analysis includes SSI. This points out to the convenience of incorporating SSI in the dynamic analysis to obtain more accurate estimates of the actual inelastic response. Simple formulas such as that proposed by Jennings and Bielak (1973) provide rapid and accurate estimates of the SSI uncoupled fundamental period, once the SSI parameters have been estimated. These parameters should also be carefully evaluated and incorporated in the dynamic modal analysis of buildings. Special attention should be paid to factors such as layering, proximity to other structures, stiffness of the foundation members, and embedment.

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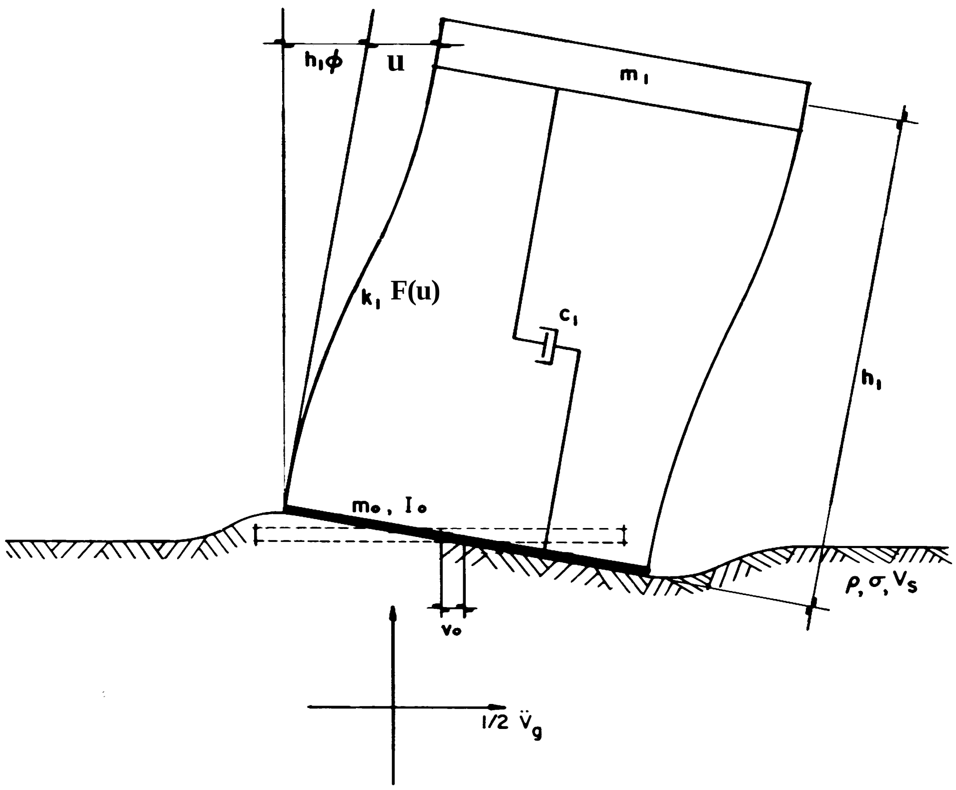

Fig 1. Model of single-story building-foundation system

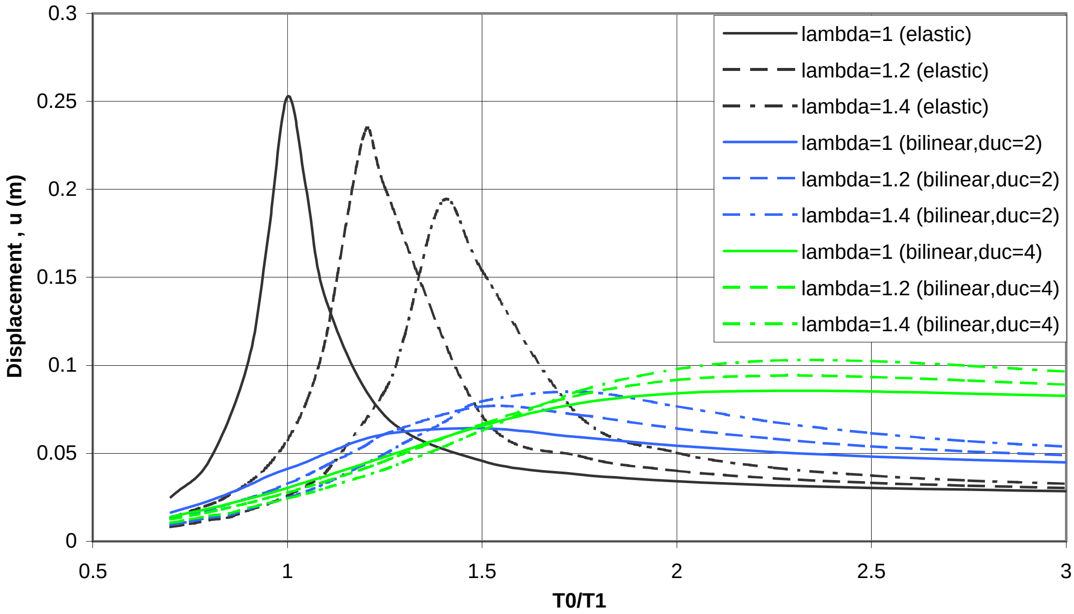

Fig. 2 Maximum inter-story drift of SSI system

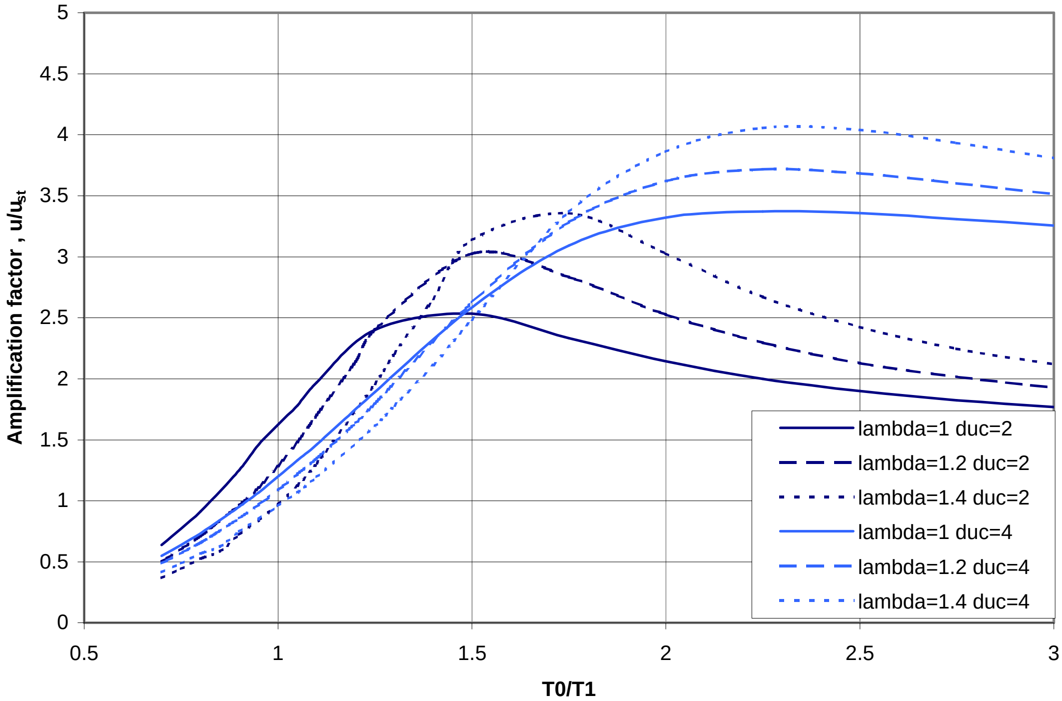

Fig. 3 Dynamic amplification factor , u/u_{st}

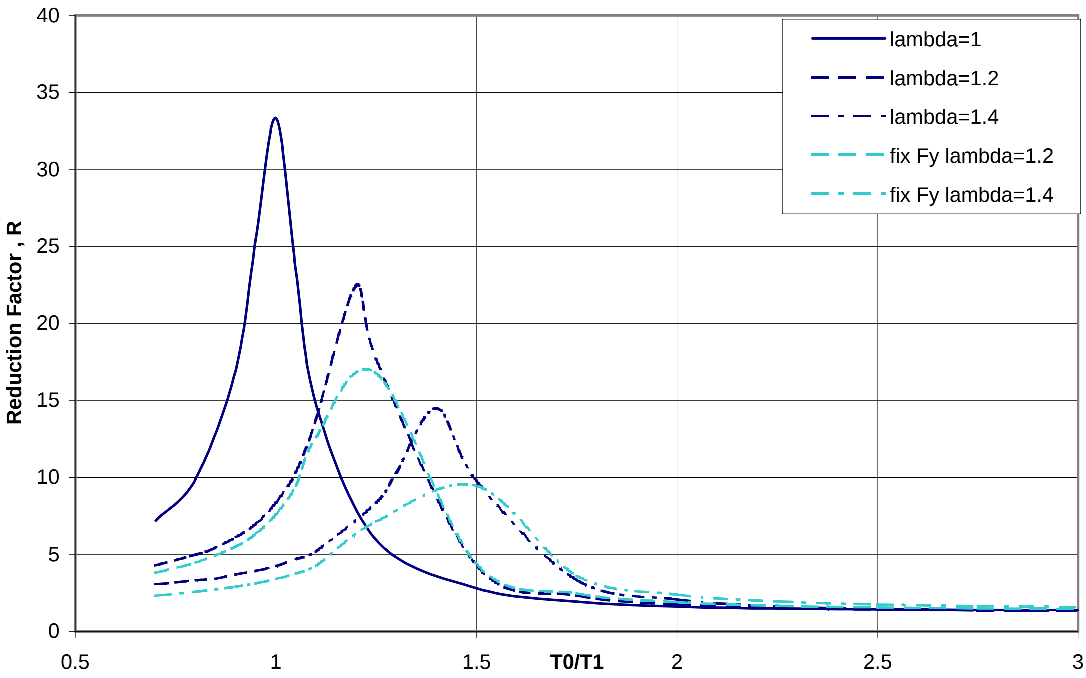

Fig. 4 Reduction factor , $R = F_{elastic} / F_{yield}$

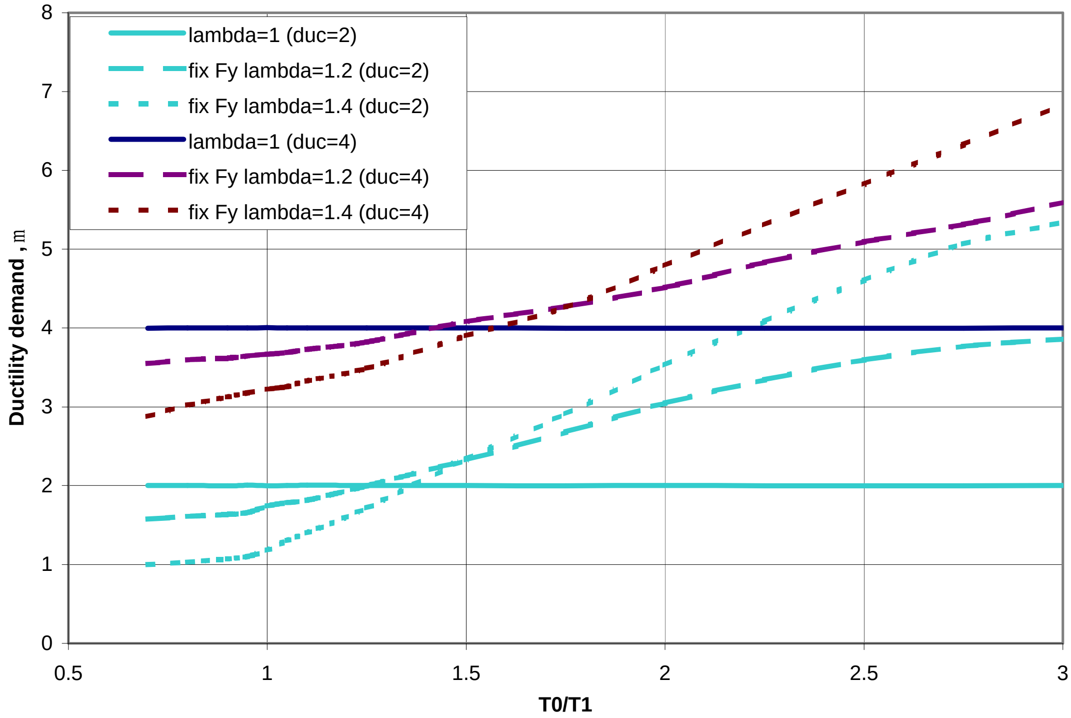

Fig. 5 Ductility demand , $\mu = u_{max} / u_y$

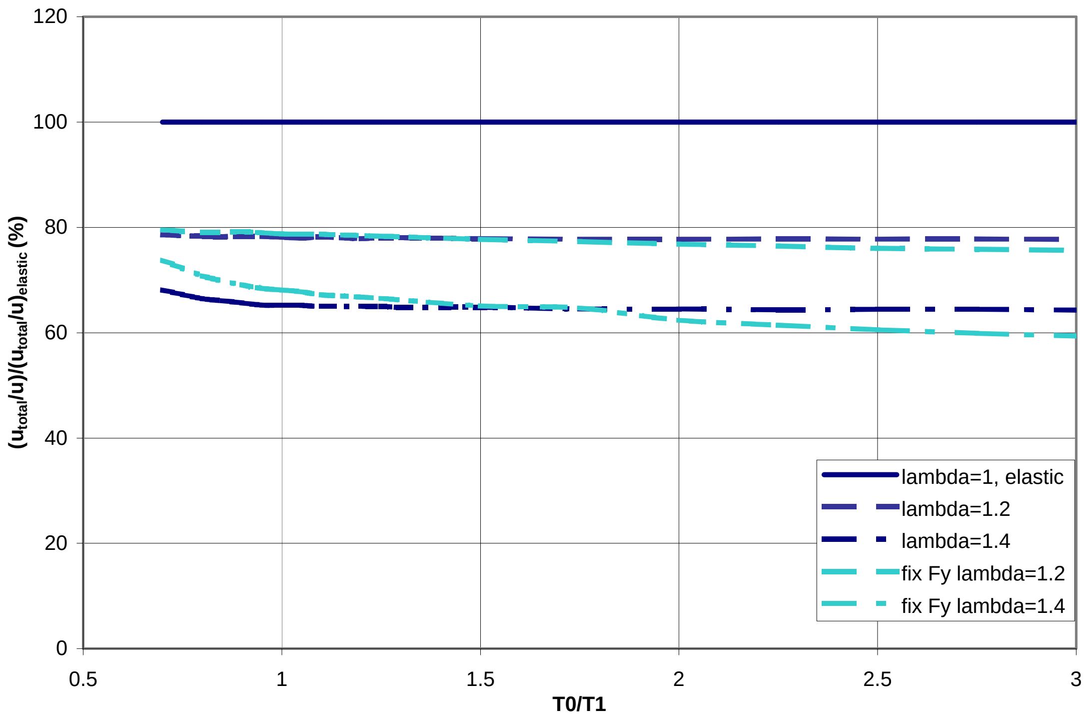

Fig. 6 Normalized total displacement , u_{total} / u with respect to corresponding elastic value

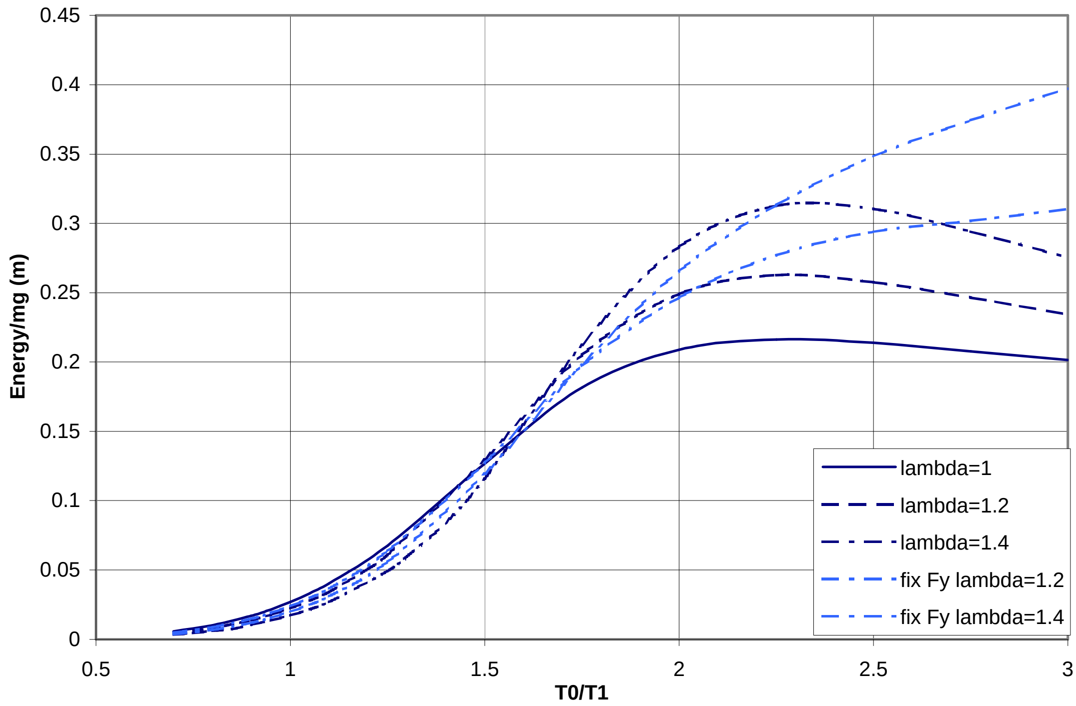

Fig. 7 Hysteretic energy per cycle

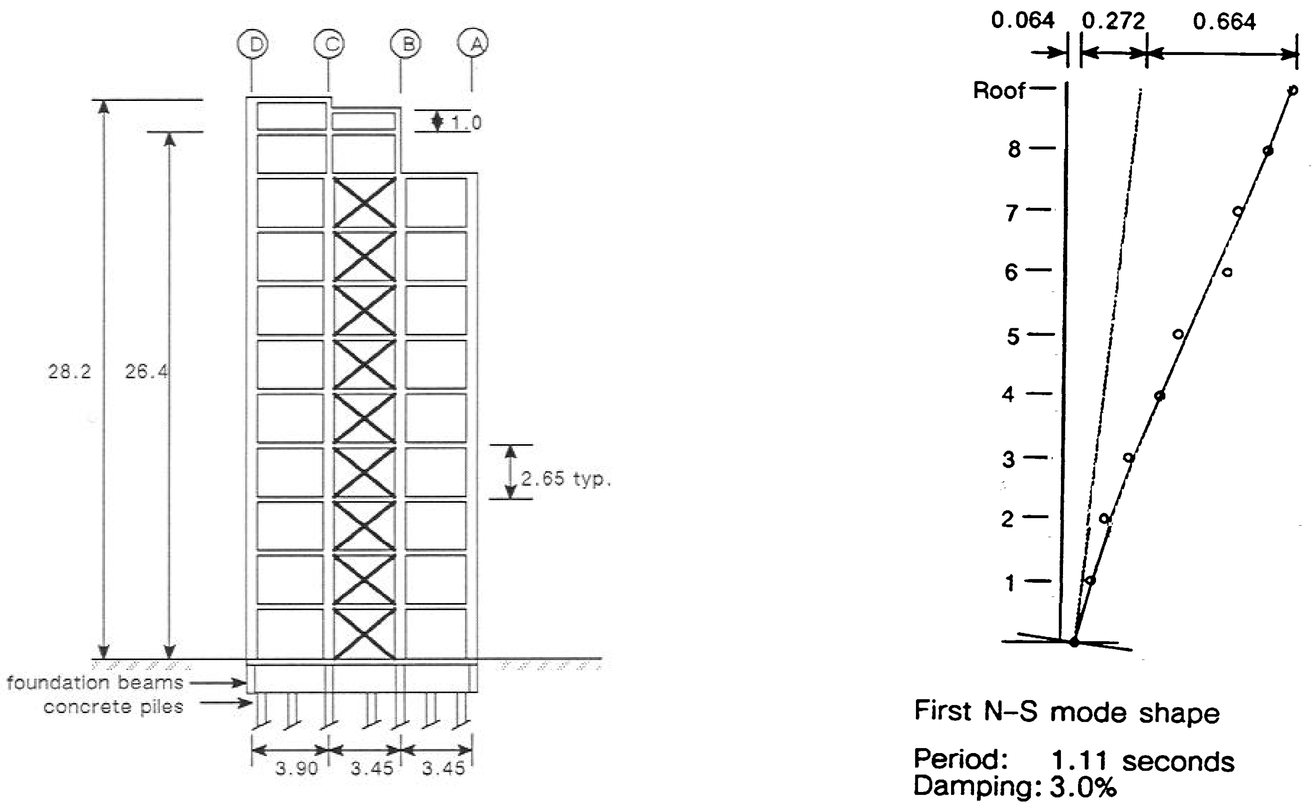

Fig. 8 Parque España building and corresponding first modal properties in NS direction (after Foutch et al, 1989)

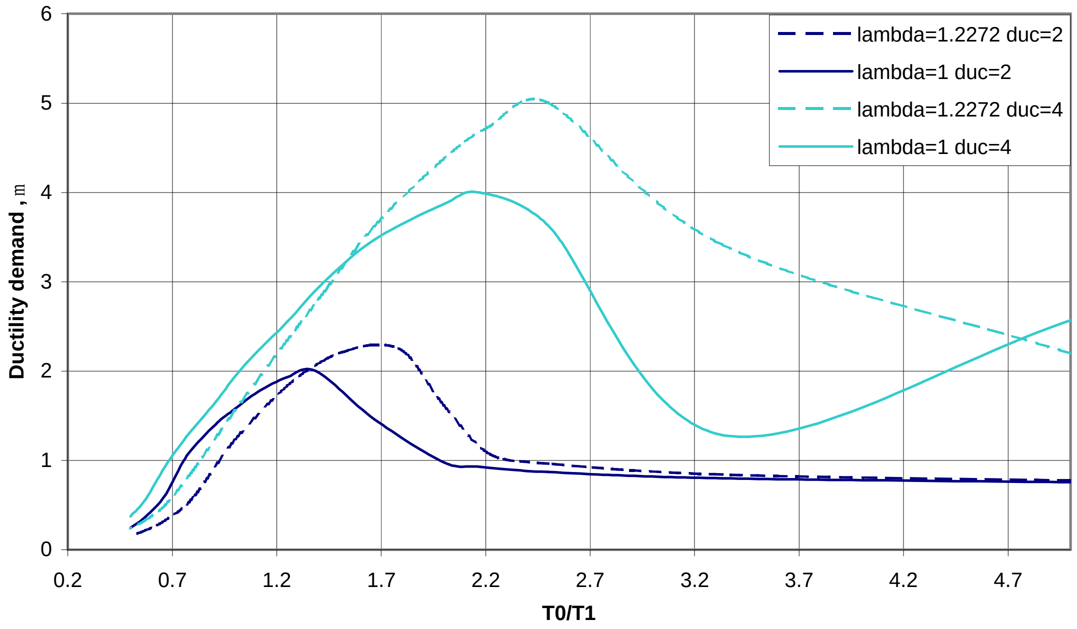

Fig 9. Ductility demand of Parque España building model

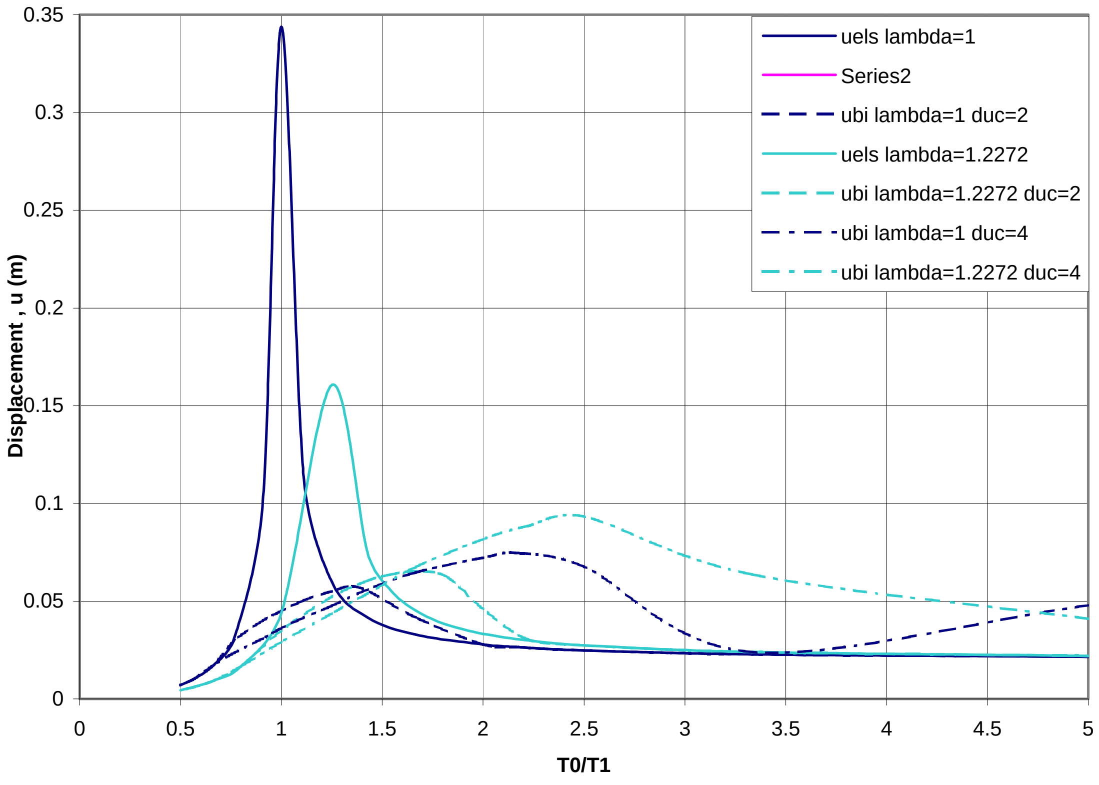

Fig 10. Maximum inter-story drift of Parque España building model

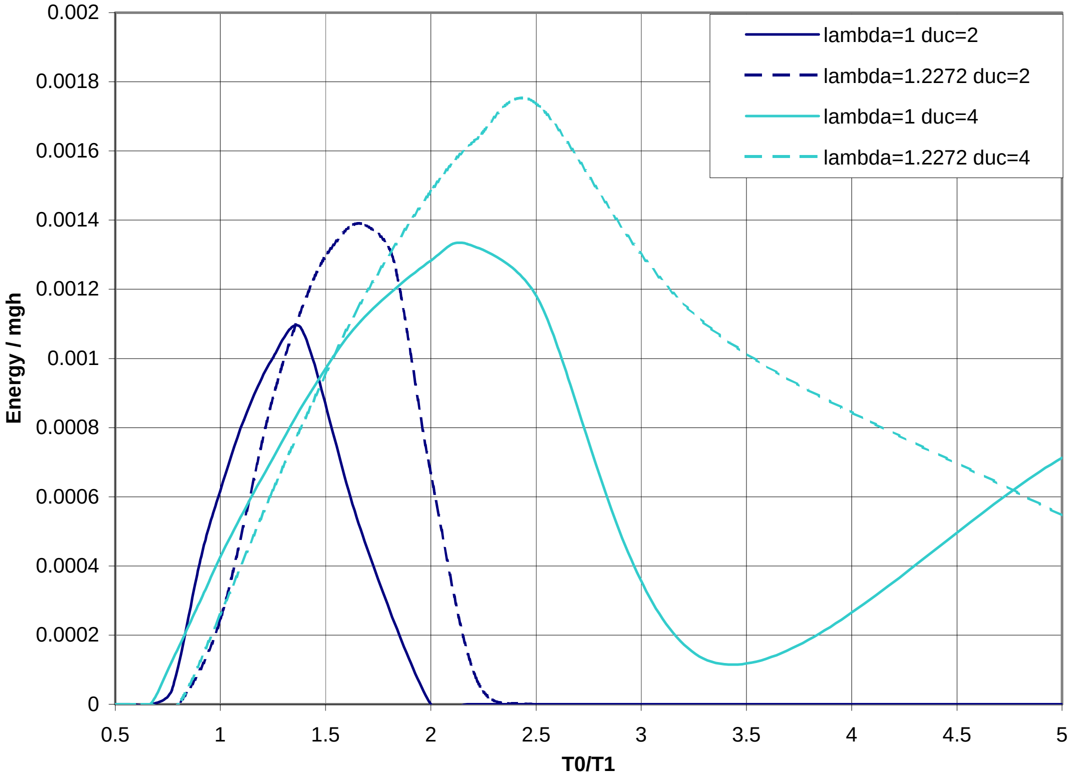

Fig.11 Hysteretic energy per cycle of Parque España building model