Inelastic response of tuned systems

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ABSTRACT: The seismic behaviour of tuned equipment-structure systems is studied. The system components are allowed to behave elastically or inelastically. The effect of various parameters such as mass ratio, yield level and frequencies on the system response to selected strong earthquake ground motion are evaluated. The results determine the limits when the response from decoupled analysis represent close approximations to the coupled system response. A decoupling criteria for inelastic systems is discussed.

INTRODUCTION

The seismic design of important and critical equipment housed in and attached to structural systems represent a difficult design problem. Critical equipment is required to remain functional during and following a major seismic event. This equipment includes emergency, communications and hospital facilities. Equipment used in the power generation, emergency power and water supply and equipment controlling hazardous materials and contaminants are also classified as critical equipment. During an earthquake, equipment located in higher floors is subjected to floor motion that is much more severe than the ground motion. It is not uncommon to design the equipment and its supports for substantial levels of acceleration.

Theoretically, the equipment can be incorporated with the structure in a single dynamic model. The complete equipment-structure model can be analyzed using available dynamic analysis methods. However, this approach is not practical at the early design stages due to the absence of information about the location, attachment points and vibration characteristics of the equipment. A more convenient analysis approach is to uncouple the equipment-structure system in situations when the response of the uncoupled system gives a reasonably close approximation to the response of the coupled system. Uncoupling the system using decoupling criteria is the code approach to the design of relatively light equipment. However, a limitation on the applicability of the code decoupling formula exist because most of the current design criteria are based on the elastic response of both structure and equipment. The National Building Code of Canada, NBCC (1985) at the present does not consider the effect of resonance conditions on the system decoupling guidelines.

The dynamic interaction between elastic primary and secondary systems has been the subject of extensive investigation during recent years (Aziz and Duff 1978, Hernried and Sackman 1984, Kiureghian et al., 1983, Newmark and Villaverde 1980, Ruzicka and Robinson 1980). The study of the behaviour and interaction of an inelastic primary system and inelastic secondary system has received little attention due to the complexity of the problem. The study of Anderson (1963), on the dynamic behaviour of two-degree-of-freedom elasto-perfectly plastic system under actual earthquake motions shows that the displacement response of the secondary mass is reduced with the decrease in the yield level of the primary spring. The use of response spectrum approach in the seismic design of nuclear power plant facilities were addressed by Newmark, 1975 and Newmark and Hall, 1979. They discussed some criteria applicable to the inelastic design procedure for structures and equipment.

The objective of this investigation is to study the seismic response of tuned equipment-structure systems. The system components are allowed to experience inelastic deformation which is the case for a major seismic event. Some critical structures are designed to behave elastically during design earthquakes. However, most structures such as buildings are expected to deform well beyond the elastic range under intense earthquake ground motion depending on the degree of ductility incorporated in the design and construction. An attempt is also made to relate the tuned systems inelastic response to the existing code decoupling criteria.

SYSTEM MODEL

A two-degree-of-freedom spring-mass system as shown in figure 1, is an ideal simple system for the preliminary investigation of the effects of coupling on the

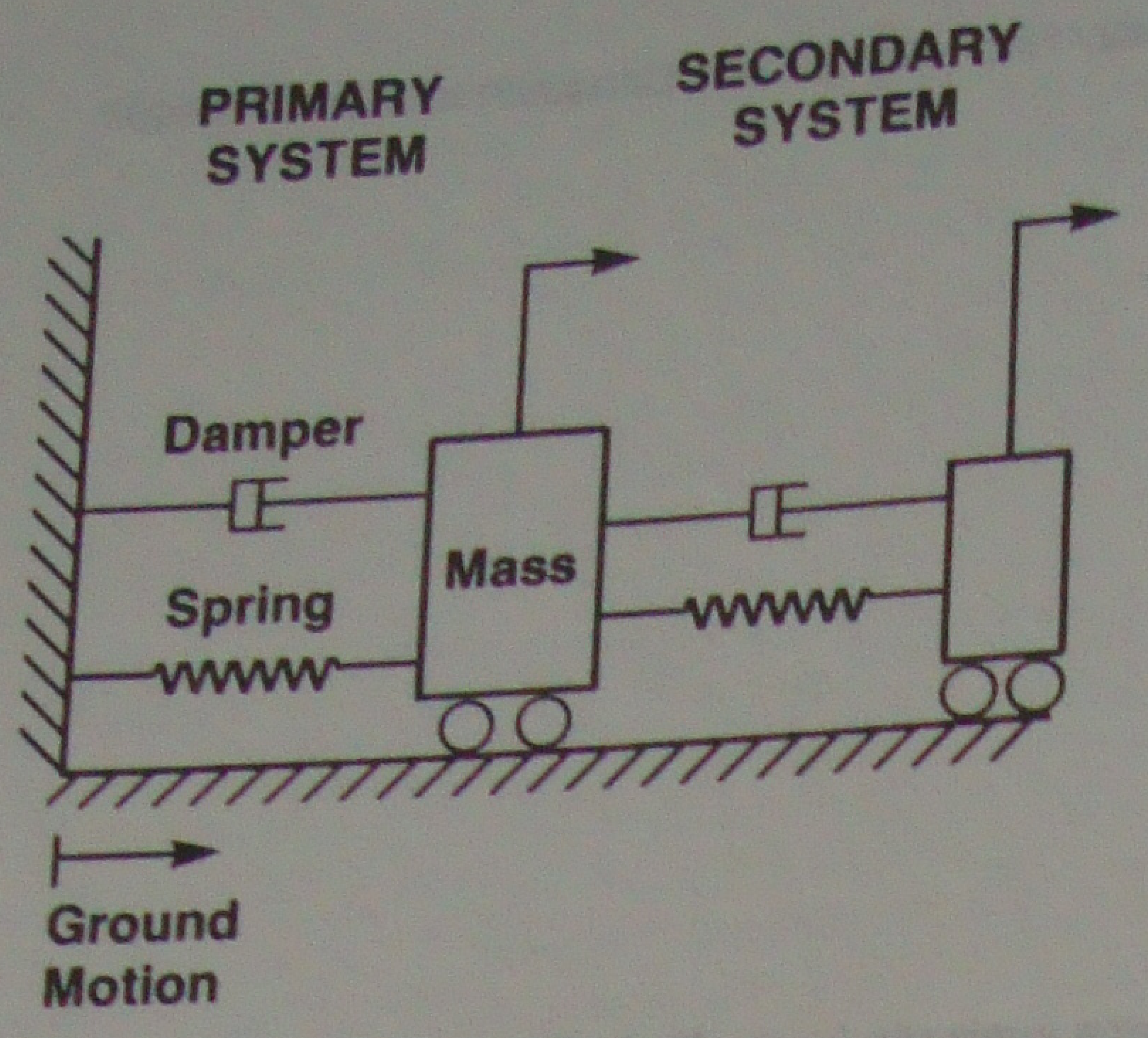

Figure 1 Simple two-degree-of-freedom model.

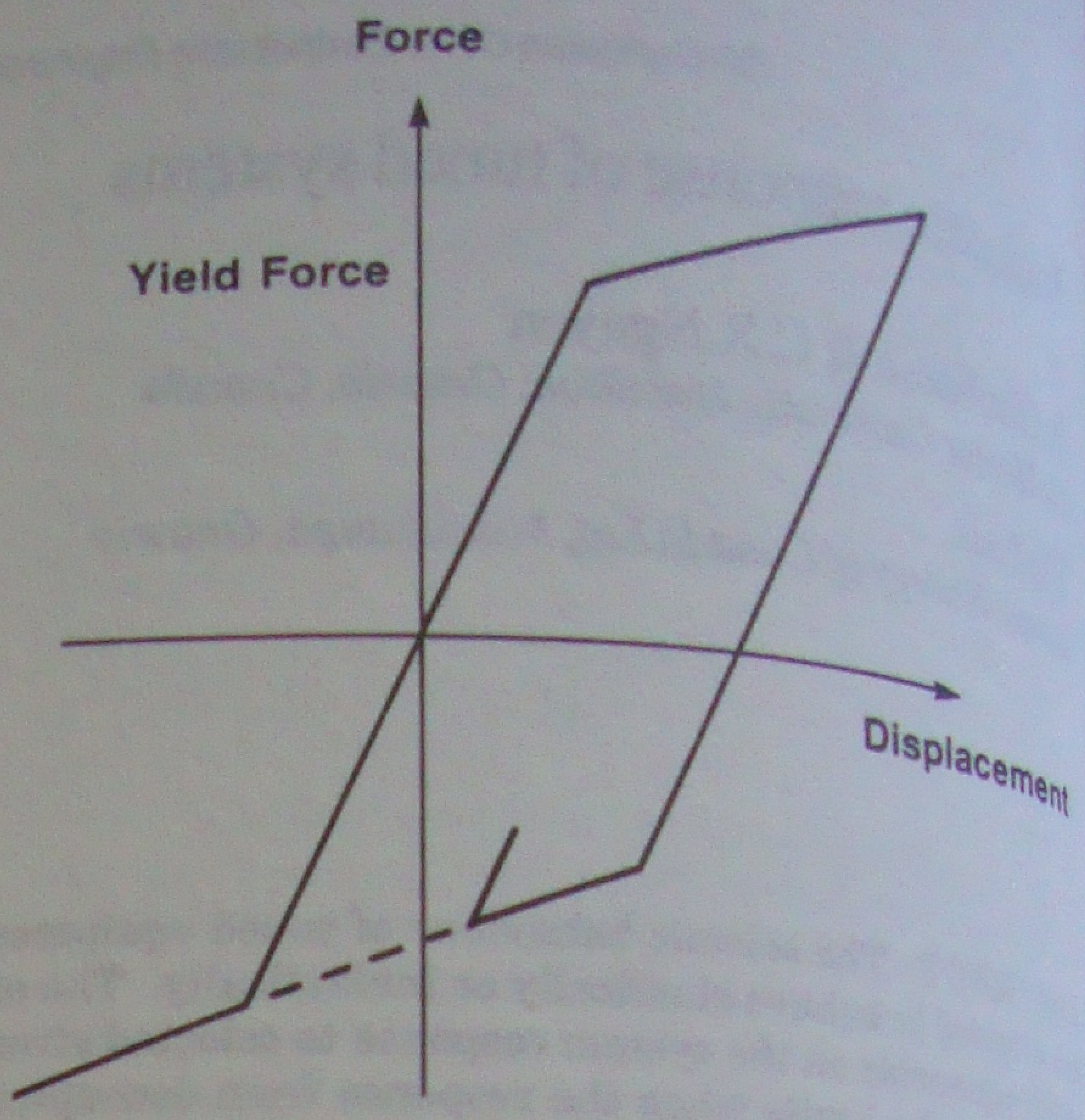

Figure 2 Bilinear load-displacement spring characteristics.

behaviour of the structure-equipment systems. For uncoupled analysis, two single-degree-of-freedom systems are considered to represent the equipment and structure systems. The response of primary system (structure) is used as input to the secondary (equipment) system. At present, the response of the multi-degree-of-freedom inelastic structures can only be obtained through the step-by-step integration method. Computer programs using step-by-step integration scheme are available commercially. However, most programs are far more complicated than is needed for this investigation. In addition, some programs cannot be easily modified for particular hysteretic loop or to generate required output parameters.

A micro-computer program is developed for analyzing the dynamic response of multiple-degree-of-freedom inelastic systems using Wilson-θ method. Among several integration methods such as Central-difference method, Constant velocity method, Newmark-β method etc., the Wilson-θ method is considered to be the simplest method, unconditionally stable, does not require special starting procedures and produces accurate response results of the system. For varying displacement ductility in the systems, the yield force of the spring is reduced to different levels, proportional to the maximum elastic spring force response for each input acceleration time history.

The analysis was conducted using a bilinear force-displacement characteristics for the spring. The bilinear model, shown in figure 2, considers the strain hardening of the material after yielding. In steel a 3.0 to 5.0% slope for the strain hardening are usually assumed for the bilinear model. In this study, a 10% slope of the inelastic stiffness curve is used to obtain the effect of strain hardening behaviour on the dynamic response. However, because of the small slope of the inelastic stiffness, the dynamic response of the bilinear model was found to be very close to the response of a model with elasto-plastic spring characteristics. Under earthquake excitation, the bilinear model does offer the advantage of being somewhat more efficient in energy dissipation through the hysteretic behaviour and more stable dynamic response.

Due to the uncertainty of the ground motion, an ensemble of records of time history has been used to determine the mean values of the response of the systems. The response ratio, defined as the ratio of the response from coupled analysis to the response obtained using uncoupled analysis can be studied for various system parameters in order to determine the criteria for decoupling in the inelastic range. The parametric study assisted in the development of practical guidelines for the design of essential and control equipment. Some of the parameters used in the investigation include mass ratios, yield level of the springs, frequency of free vibration, and ground motion characteristics.

INPUT GROUND MOTION

Actual earthquake records are used as input ground motion in the numerical analysis in order to take into account the uncertainty in real characteristics of ground motions. However, to reduce the volume of computations to a reasonable amount, only limited number of widely differing strong motions are used with different frequency responses and different group of acceleration-velocity related zone as listed in table 1. The selected ground motions cover a variety of situations regarding site conditions, intensity, distance to fault and duration of motion. The 1985

National Building Code of Canada classifies the range of the ratio of the peak horizontal ground acceleration to the acceleration due to gravity and the ratio of the peak horizontal ground velocity to a velocity of 1.0 meter/second into six zones. The earthquakes are divided into three groups where the acceleration-related seismic zone is greater than, equal to, or less than the velocity-related seismic zone. For each group, the dynamic response of the system may have different amplification factor and different dynamic behaviour. The three earthquakes considered cover the range of Z_a/Z_v less than, greater than and equal to unity. The actual earthquakes time histories are normalized so that the acceleration response of the single-degree-of-freedom system will be the same for each earthquake. The ground acceleration time histories are normalized to spectral acceleration of 1.0 g at the period of the tuned system and the applicable damping ratios (β of 3.0% and 5%).

Table 1. Ground Motion Input Data

Location and Component	Magnitude	Total Duration (sec)	Maximum Displacement (cm)	Maximum Acceleration (cm/sec^2)	Z_a/Z_v
ElCentro (1940) S 90 W	6.3	53.48	19.8	210.1	.67(<1)
Parkfield (1966) N 65 W	5.6	30.42	4.7	264.3	1.67(>1)
San Fernando (1971) S 74 W	6.6	41.74	10.8	1054.9	1.00

The first ground motion considered is the El Centro Earthquake S90W component of May, 1940. This is a typical white noise type California earthquake excitation that has been used quite extensively in earthquake engineering studies. According to the National Building Code of Canada, this ground excitation has the Acceleration zone lower than the velocity zone.

The Parkfield earthquake of June, 1966 with N65W component, is a high frequency response ground excitation. Most of the strong motions occur at the first five seconds and then die out very quickly. The response spectrum of the earthquake shows a narrow frequency content around 0.2 to 0.4 seconds. In this earthquake, the acceleration zone is found to be higher than the velocity zone.

The San Fernando valley earthquake of February, 1971 is a well known earthquake. The earthquake time history component S74W is recorded adjacent to the Pacoima dam abutment, inside an instrument shelter with maximum peak horizontal ground acceleration over 1.0 g. The acceleration-related seismic zone of this ground motion is the same as the velocity-related seismic zone.

RESULTS

The nonlinear numerical analysis was conducted using various ground motions for a wide range of system parameters. Solutions were obtained for various mass ratios, critical damping ratios, system yield levels and frequencies. The quantity of interest is the acceleration response ratio which is defined as the ratio of the maximum acceleration obtained using the coupled analysis to the maximum acceleration from the decoupled analysis approach. Typical results are shown in figures 3 to 6. The four figures represent

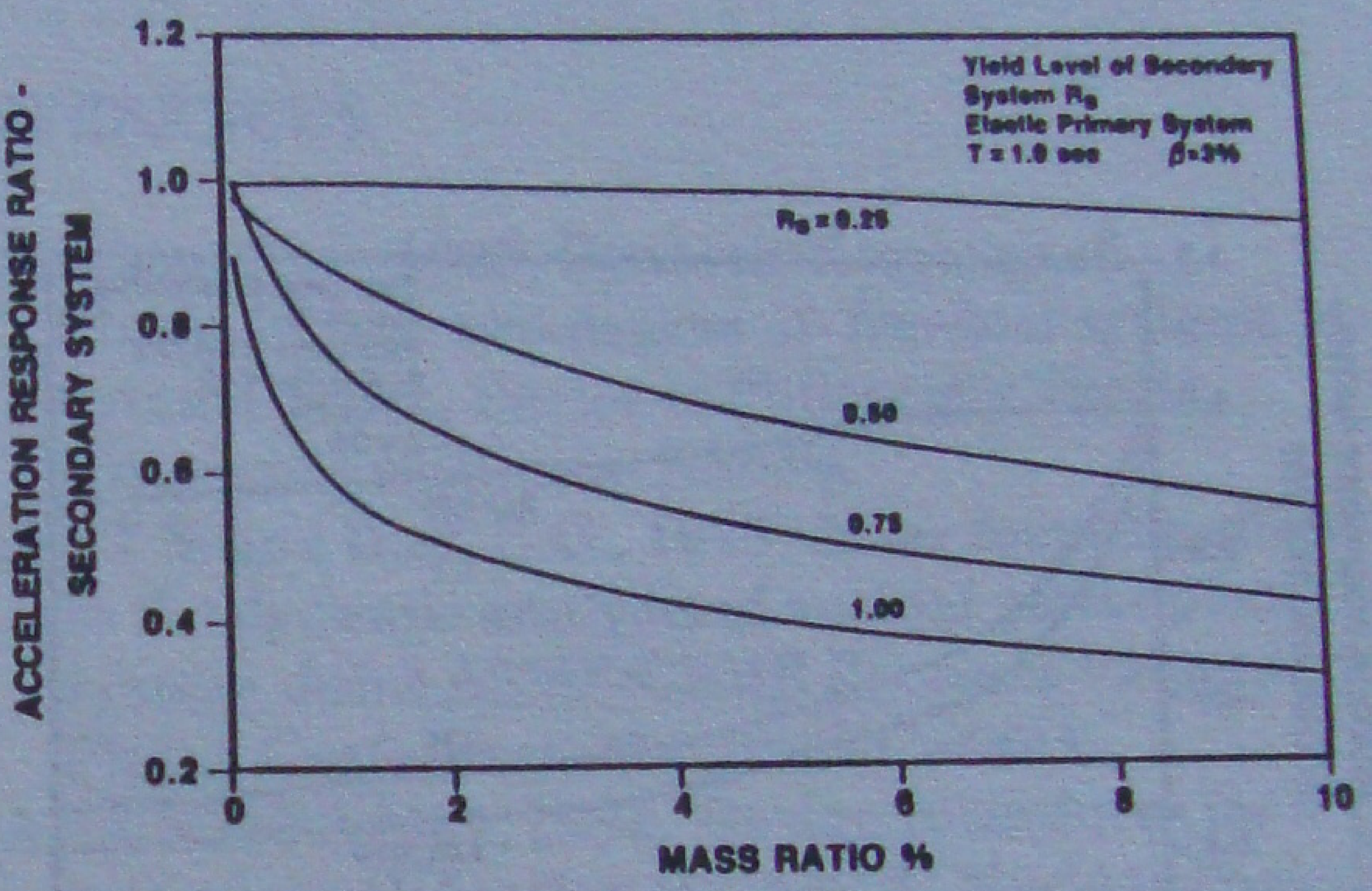

Figure 3 Acceleration response ratio variation of secondary system with elastic primary system.

the effect of the mass ratio and yield levels on the response acceleration ratio of the secondary system. The tuned system period is unchanged at 1.00 sec and the system's critical damping ratio is taken to be 3%. Cases of primary yield levels Rp = 1.00 (elastic), 0.75, 0.50, 0.25, are shown in figures 3, 4, 5 and 6 respectively. It can be observed that by increasing the ductility of the secondary system, its response ratio approaches unity which is the case of a decoupled system.

From an engineering point of view, a limitation on the mass ratio can be obtained based on restricting the response ratios of the system to an established value. An over estimation error of 25% and an under estimation error of 15% in the response ratios are considered consistent with the current seismic design knowledge. From the results of the three specific periods in different ranges of the response spectrum, a mass ratio in the range of 0.1 to 1.0% is chosen to be the limit for decoupling the tuned elastic system. This conclusion

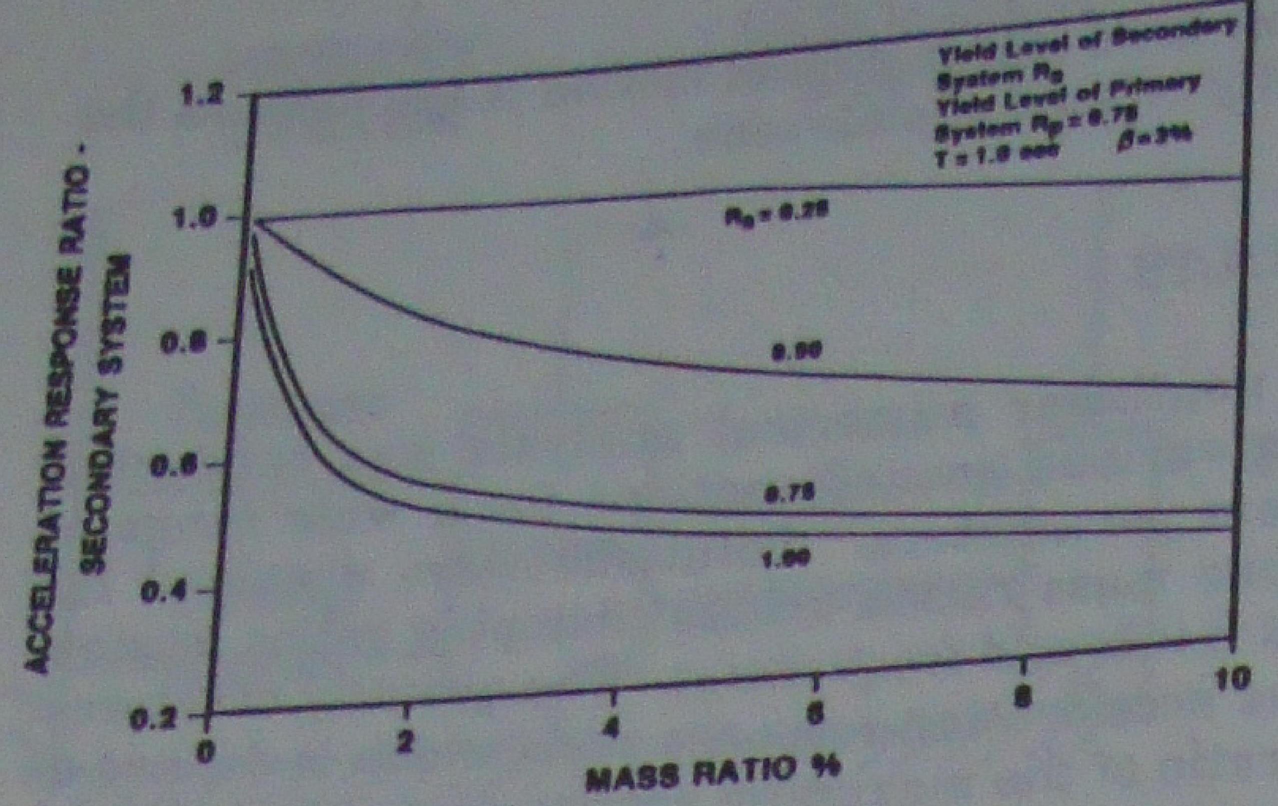

Figure 4 Acceleration response ratio variation of secondary system with primary system of yield level of 0.75.

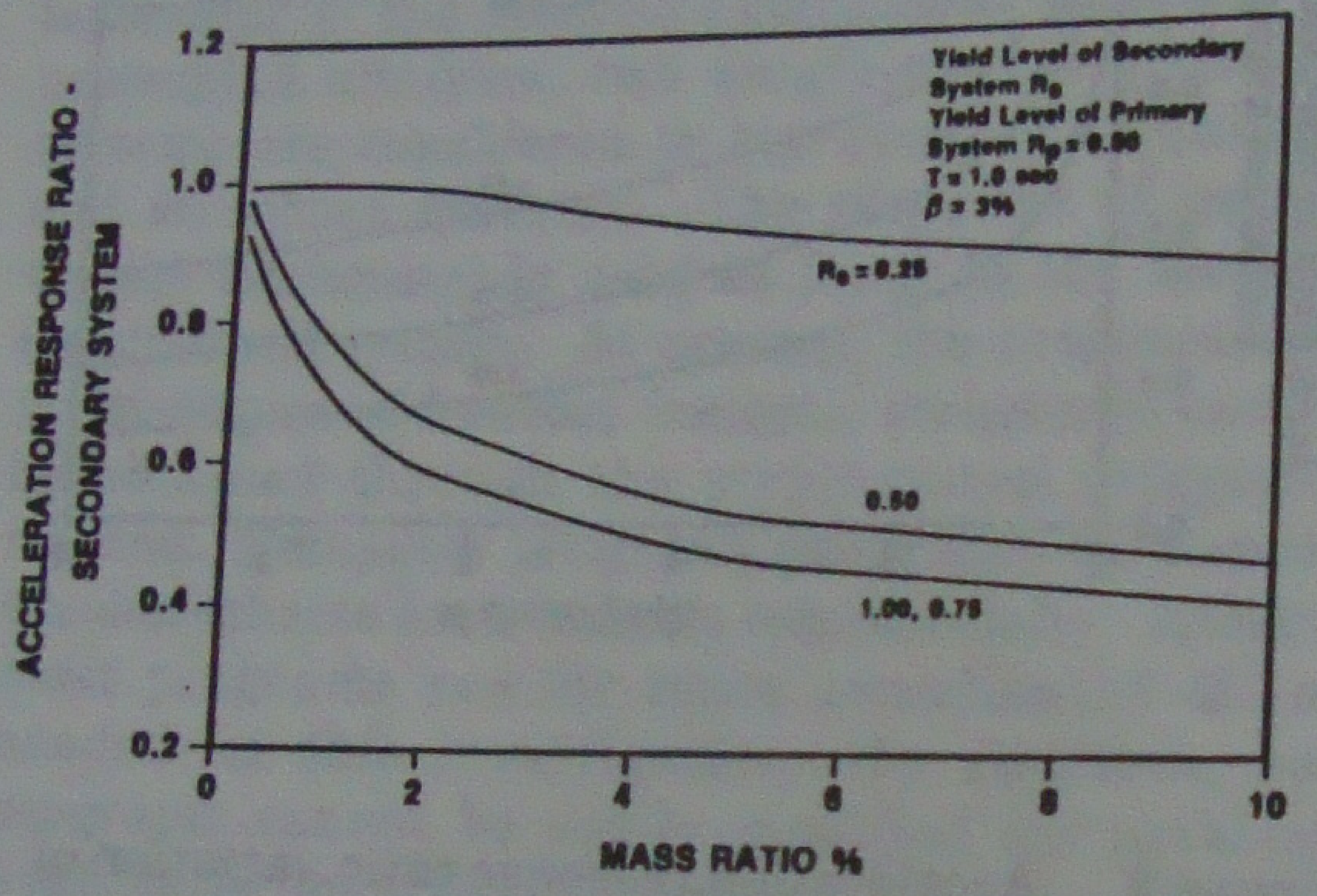

Figure 5 Acceleration response ratio variation of secondary system with primary system of yield level of 0.50.

is consistent with the existing decoupling criteria. However, the National Building Code of Canada has allowed the use of a maximum of 10.0% mass ratio as the limit for decoupling the equipment or the secondary system even for the resonant condition where the coupling effect has the most impact on the system. The amplification factors that are expressed in terms of the horizontal force factors S_p are listed in table 4.1.9.D in the 1985 NBCC for a specific secondary system (equipment) such as wall elements, appendages, machinery, fixtures, tanks and pipes.

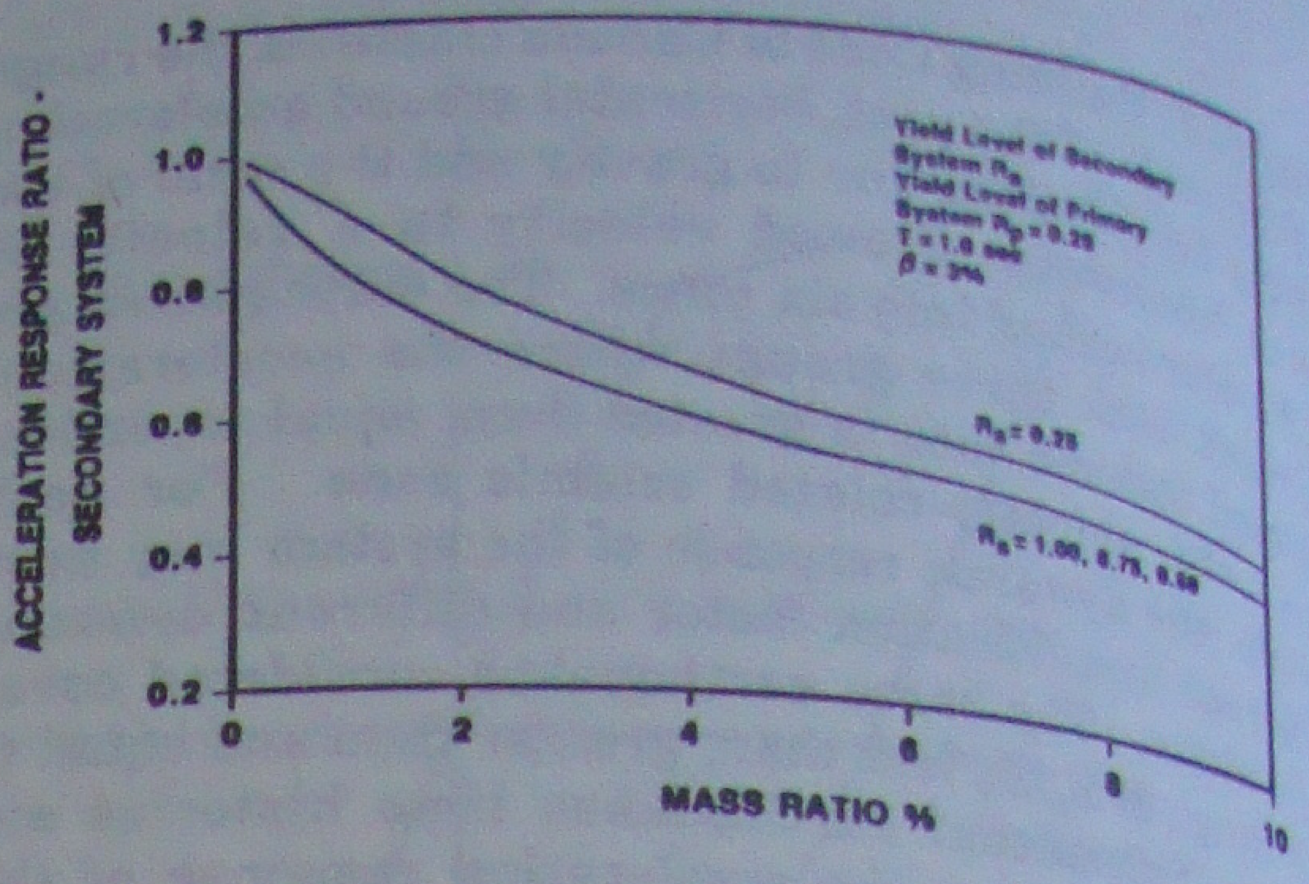

Figure 6 Acceleration response ratio variation of secondary system with primary system of yield level of 0.25.

According to the Code Provision, there are no information concerning damping ratio, yield level or maximum allowable ductility ratio of the systems. The amplification factors for design are presented mainly in two cases: the resonant case with an amplification factor of 10.0 and off the resonant case with an amplification factor of 2.0 or less. If both the equipment and the structure respond elastically such as ornamentations attached to the unreinforced masonry building, the amplification factor of 10.0 obtained from the Code is applied. The average response of the secondary system (equipment) under the cases considered leads to acceleration amplification factors of 4.8, 2.0 and 0.04 for an elastic tuned system with a mass ratio of 10.0%, damping ratio β of 3.0% and the period T of 0.2, 1.0 and 10.0 seconds respectively. Amplification factors are found to be 18.0, 6.0, 0.08, for elastic tuned system with the mass ratio of 0.1%. The fundamental period of masonary structures falls into the range of 0.2 sec. In this case, the response of the secondary system per NBCC 1985 may be over estimated by up to approximately 100.0% for a tuned elastic system with 10.0% mass ratio. On the other hand, the National Building Code may under estimate the design force acting on elastic equipment by up to approximately 44.0% for the case of tuned elastic system with 0.1% mass ratio and 3.0% damping ratio.

Based on the evaluation studies of elastic system response two possible changes for the tuned equipment response provision in the National Building Code are proposed. The first proposed change is aimed at providing the limit of the mass ratio for decoupling the tuned elastic equipment. It is recommended that the maximum mass ratio that is required for decoupling the tuned elastic equipment from the main structure may be reduced to a lower value of 0.1 to 1.0% in order to be consistent with other codes and to obtain proper seismic design forces for the equipment. Second, the amplification factors may need to be changed in considering the dynamic characteristics and behaviour of the structure (fundamental period, class of structure, etc.) so that an appropriate design force for the equipment could be estimated.

In general, the decoupling criteria of elastic system may apply for inelastic system, however, in some cases, the coupled analysis may not be necessary. For a system with bilinear spring stiffness characteristics, a higher mass ratio may be used for decoupling the system due to small interaction between the primary and the secondary systems. The proposed decoupling criteria limits the change of the coupled response from the uncoupled response to an acceptable level of error from −15.0% to +25.0%. Due to different effects of the yield levels of primary and secondary springs, the decoupling of the bilinear system may be considered in two cases. In the first case, the primary spring behaves elastically and the secondary spring is in the inelastic range. In this case, the decoupled analysis can be performed if the mass ratio is lower than 2.0, 3.0 and 4.0% for equipment with 0.75, 0.50 and 0.25 yield level. In the second case, the primary structure behaves plastically and the secondary system may respond in the elastic or the inelastic range. The decoupling mass ratio is 1.0, 1.5, 2.0% for bilinear structure with 0.75, 0.50 and 0.25 yield level respectively. For simplicity, a 1.0% of the mass ratio may be used as the limit between coupled and uncoupled analyses for tuned system that experiences inelastic behaviour.

CONCLUSIONS

Based on the numerical studies of tuned inelastic systems response to selected earthquake time histories, the following conclusions are arrived at.

- The most important parameters governing the response of the secondary system are the mass ratio and the yield level of the system components.

- A different critical mass ratio may be suggested at each yield level of the primary system for decoupling the inelastic tuned system.

- A 1.0% mass ratio appears to be a reasonable decoupling criteria of the tuned system when both primary and secondary systems respond inelastically. This mass ratio value may be low for the system with inelastic equipment, but for simplicity, only one mass ratio is suggested for the whole range of elastic and inelastic behaviour with various the yield levels.

- A higher mass ratio may be used for decoupling the inelastic equipment from the elastic structure.

- The decoupling criteria of tuned system in the 1985 National Building Code of Canada is arbitrary and may not be conservative for the structure and may be too conservative for the equipment or attachment. It is concluded that 10.0% mass ratio, as suggested by the Code is appropriate for decoupling a heavily inelastic equipment attached to elastic structure system within the range of parameters considered. In general, for the structure with large inelastic deformation, the 10.0% mass ratio for decoupling may introduce very low response in the equipment but the response of the structure may be underestimated due to neglecting the interaction between the equipment and the structure.

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