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PRELIMINARY DESIGN OF BASE-ISOLATED STRUCTURES

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SUMMARY

Those responses to design earthquakes which are important for the preliminary design of base-isolated structures are discussed and some responses are given for a wide range of isolator parameters. Isolators considered are either linear, with moderate or high-level velocity damping, or are bilinear in their resistance to cyclic deformations. Responses considered are; the isolator shear force and deformation, the distribution of structural loads and of shear forces at various levels, and the loads on resonant equipment and facilities.

INTRODUCTION

Structures are designed to prevent unacceptable levels of structural, non-structural and content damage or malfunction during design-level earthquakes. In order to assess the merits of base isolation for a particular structure, and to make a selection from the available isolator parameters, designers require approximate values for various maximum responses during design earthquakes. Responses considered here are; inertia loads throughout the structure, the resulting shears throughout the structure, and the enhanced inertia loads on resonant components and facilities which are located at various levels of the structure. Structural deformations follow from the shear distribution. Particular attention is given to isolator deformations.

Responses to design earthquakes are considered for structures with either linear isolators which include moderate or high-level velocity damping, or with bilinear isolators which include components which yield or which slide with significant friction. The achievement of the flexibility and the bilinear resistance for such isolators is discussed extensively in the literature.

Features of the "Modal" Responses of Isolated Structures Earthquakes generate accelerations of the masses of isolated structures which can be resolved into the accelerations of a set of vibrating modes, somewhat similar to the modal accelerations of non-isolated structures. While the "modes" of a structure with bilinear isolation are not amplitude-independent and non-interacting they may still be used effectively for many design purposes.

At near-maximum response levels the first mode of an isolated structure has the approximate period, damping, shape and load distribution which it would have if the structure above the isolator was rigid. Since the first mode of a well-isolated structure completely dominates the base level shear force and relative displacement, these may be obtained from a one-mass model, with a small correction for high structural flexibility if required.

Again at near-maximum response levels, the important isolated modes above the first have the approximate periods, dampings, shapes and load distributions which would occur with an isolator of zero shear resistance.

With linear isolators all the above modal features remain the same throughout the whole range of response levels.

The level of response of the first mode depends on the effective flexibility and damping of the isolator. The levels of the responses of important modes above the first are strongly influenced by the isolator parameters. When a linear isolator has moderate damping the higher modes have much lower participation factors, and hence responses, than the corresponding modes of the structure without isolation. If the linear isolator is given high velocity damping the higher mode responses are substantially increased but usually remain below the levels for the unisolated structure.

Bilinear isolation usually causes strong modal interactions which result in a large transfer of energy from the first to higher modes. This results in much greater responses of the important higher modes than occurs with linear isolation. These higher mode responses may exceed substantially the levels which would occur without isolation.

The following discussion of the preliminary design of isolated structures flows on from the earthquake response features outlined above.

STRUCTURES WITH LINEAR ISOLATORS

With linear isolators the mode-1 controlled maximum base shears and displacements are given by the acceleration and displacement response spectra of the design earthquakes; where base shear is the product of spectral acceleration and structural mass. Inertia loads are dominated by the almost-equal mode 1 accelerations of the structural masses. High isolator damping may result in significant higher-mode contributions to loads and to higher-level shears.

The designer may have chosen high levels of isolator velocity damping, 20% to 30%, in order to limit base displacements. If the resulting substantial increase in higher mode responses is a serious problem most of the increase can be prevented by fixing one end of the velocity dampers via components of appropriate flexibility.

The severe side-sways which wind storms may give to some structures with linear isolators may prevent their use in some cases.

STRUCTURES WITH BILINEAR ISOLATORS

Base Shears and Displacements With bilinear isolators, and with "El Centro" type design earthquakes, the base-level shears and displacements may be estimated from the curves of Fig 1. Here isolator stiffnesses and yield levels are related to the structural mass and weight by periods and by yield ratios, as indicated.

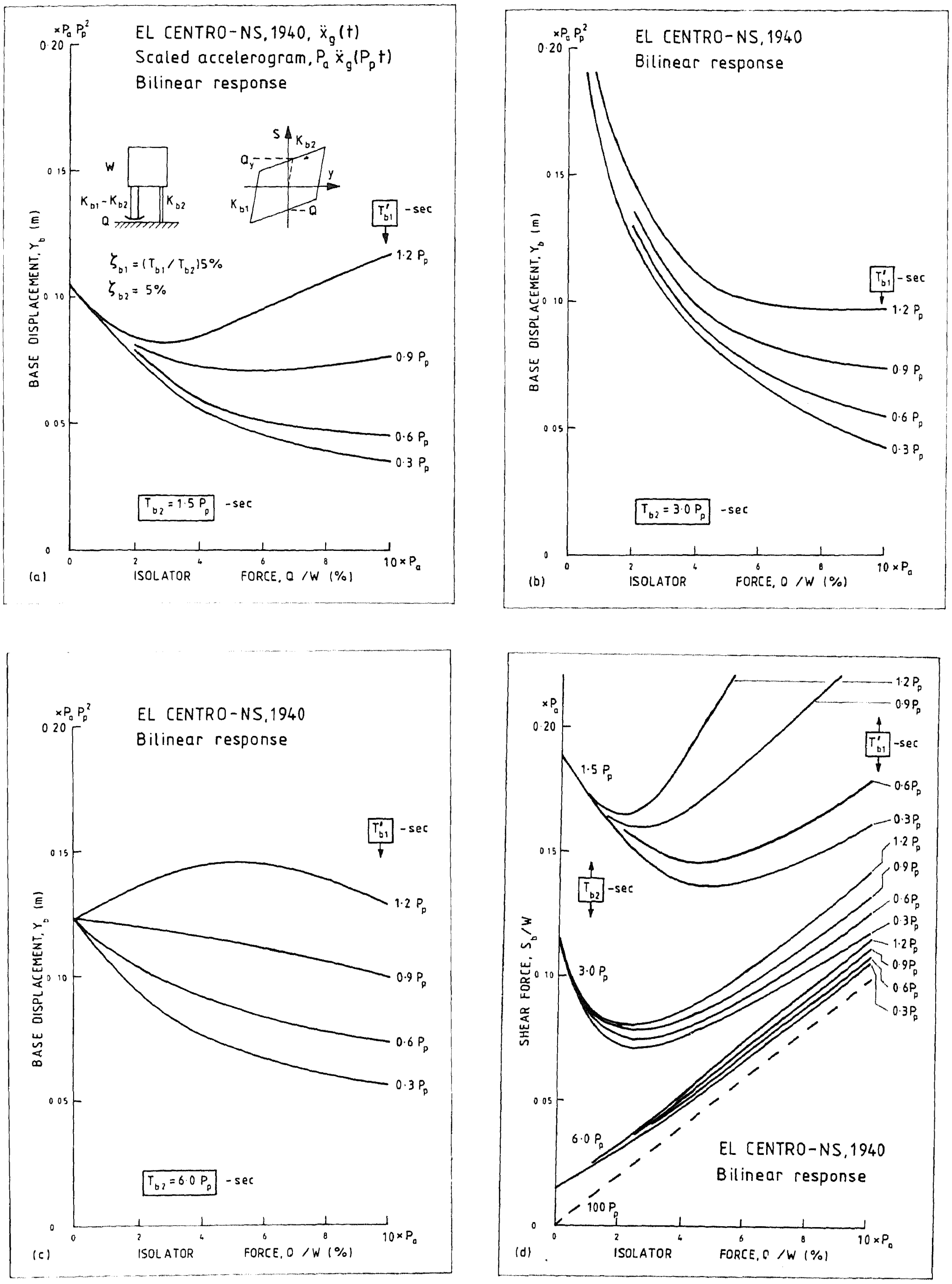


Fig 1: Maximum displacements and shear forces for a bilinear isolator during the scaled earthquake, El Centro, S 0°E, 1940.
$T_{b1} = 2\pi\sqrt{(M/K_{b1})}$, $T_{b2} = 2\pi\sqrt{(M/K_{b2})}$.

An accelerogram amplitude scaling factor P_a, and a time scale factor P_p, are introduced to provide for design earthquakes with spectra differing from those for El Centro, S 0°E, 1940. The factors P_a and P_p are chosen to match the El Centro earthquake spectra to the design earthquake spectra in the general vicinity of the mode-1 effective period T_e and damping ζ_e. These may be approximated by using the secant stiffness and the loop-area damping for the maximum isolator displacement, as follows;

$$T_e \approx 2\pi \sqrt{(M/K_e)} \qquad (1)$$

$$\zeta_e \approx A_b/(2\pi\, A_L) \qquad (2)$$

where $K_e = S_b/Y_b$

S_b, Y_b = target base shear, target base displacement

A_L, A_b = area under loading curve, area of bilinear loop

The derived values of P_a and P_p are applied to the curves of Fig 1 to obtain approximate values of base, and hence also isolator, maximum displacement and shear during the design earthquake.

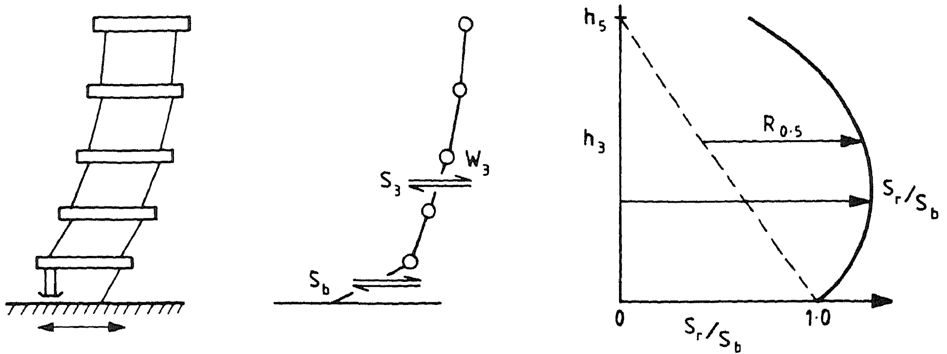
As an example let T_{b1}, T_{b2} and 100 Q/W (as defined in Fig 1) be 0.6 P_p sec, 1.5 P_p sec and 5 P_a %. Also assume that El Centro scaling values of $P_a = 1.5$ and $P_p = 1.25$ match the El Centro Spectra to the design spectra for the estimated values; $T_e = 1.5$ sec and $\zeta_e = 30\%$. Then from Figs 1(d) and 1(a) the maximum base shear and displacement during the design earthquake are;

$$S_b = 0.147\ WP_a = 0.22\ W;\quad Y_b = 0.055\ P_a\, P_p^2 = 0.13\ (m)$$

(Substitution in Eq 1 gives $T_e = 1.53$ sec). When the design and the El Centro earthquakes are of very different type (for example the design earthquake may be much more impulsive or alternatively much more periodic), then it may be appropriate to compute base shears and displacements directly using a single-mass model. Alternatively the isolator displacements may be estimated by successive use of Eqs 1 and 2 and the design earthquake displacement response spectrum. Base shear is then obtained from the isolator load-displacement curve.

Shear Distribution over Structural Levels A uniform 5-mass shear-deformation structure, with a bilinear isolator, is shown in Fig 2(a). The relative location of level shears and masses are defined in Fig 2(b), and a typical distribution of level shears is shown in Fig 2(c). The base shear S_b is given by Fig 1(d) for scaled El Centro accelerations. The dotted line gives the mode 1 shear distribution; it is triangular for a uniform continuous structure. The increase in shears above the mode 1 values are due to the loads of higher modes. They do not increase the base shear since the higher mode shears approach zero at the base level. The factor $R_{0.5}$ has been defined to represent the contribution of higher modes to the structural shear at the level of the centre of gravity of the structure. This mid-height shear exceeds the base shear whenever $R_{0.5}$ exceeds 0.5.

Table 1 gives values of $R_{0.5}$ when a uniform 5-mass shear structure, with a bilinear isolator, is subject to the El Centro earthquake. The $R_{0.5}$ values for a scaled El Centro earthquake are obtained by multiplying the isolator periods and yield ratios by the factors which are used in Fig 1. The structural flexibility parameter T_1, used in Table 1, is the first period of the structure when the isolator stiffness K_b equals an intermass stiffness K.



(a) Structure (b) Model (c) Shear distribution

Fig 2: Distribution of shears for a uniform 5-mass shearing structure with a bilinear isolator higher-mode factor $R_{0.5} = 0.5\ (S_3 + S_4)/S_b$.

Table 1: Shear distribution factor, $R_{0.5}$, for El Centro, S 0°E, 1940.

T_{b2} →	1·5					3·0					6·0					
Q/W →	2		5	10		2	5	5	5	10	2		5	10		
T_{b1} →	0·3	0·9	0·6	0·3	0·9	0·6	0·3	0·6	0·9	0·6	0·3	0·9	0·6	0·3	0·9	T_1 ↓
$100 \times R_{0.5}$	3	1	8	37	6	4	57	31	12	42	99	53	83	108	27	0·3
	8	13	19	35	14	16	60	51	39	63	111	58	85	80	69	0·6
	8	13	25	48	21	20	80	63	41	56	97	98	91	98	57	0·9

Table 2: Trends in the shear distribution factor, $R_{0.5}$.

Q/W →	2	2	2	5	5	5	10	10	10	
T_{b1} →	0·3	0·6	0·9	0·3	0·6	0·9	0·3	0·6	0·9	T_{b2} ↓
$100 \times R_{0.5}$	5		10		20		40		15	1·5
		15		70	50	40		60		3
	100		80		90		90		60	6

Some general trends in Table 1 are seen more readily in the simplified Table 2. When the trends in base shears, base displacements and higher mode response levels are compared, as isolator parameters are changed, it is seen that the most favorable values for the 3 responses cannot be obtained simultaneously. The trends shown by the figures and Tables should assist a designer to select isolator parameters which will give compromise responses which are appropriate to the design requirements.

Resonant Component Responses When a component has the same period as a structural mode it behaves as a resonant appendage and it may have substantially higher accelerations than its supports. Resonant appendage accelerations are the product of the driving mode acceleration at its location and a resonant magnification factor. This resonant acceleration will be combined with any other acceleration of the component support, but appendage responses are usually dominated by the resonant acceleration.

Resonant appendage magnifications are increased by low values of appendage and modal damping. For appendage and structural dampings of about 5%, and for regular structures on typical bilinear isolators, mode 1 is likely to give a resonant magnification of about 2 and mode 2 is likely to give a magnification of about 4.

The acceleration responses of important higher modes and the associated resonant appendage magnification factors may be summarized with the assistance of tables similar to Table 1 or Table 2.

The acceleration responses of resonant facilities will sometimes be an important factor in selecting an acceptable level for the acceleration responses of the higher modes of an isolated structure.

DISCUSSION

Important modal features which assist in the study and the preliminary design of a wide range of base-isolated structures have been outlined. Quantitative results have been presented for some important responses of simple regular structures with a wide range of isolator parameters.

Where structures with bilinear isolators have important higher mode responses these responses are best expressed as ratios of appropriate mode 1 responses. This simplifies their description since an important feature of higher mode responses, with bilinear isolators, is that their input is dominantly from the actions of mode 1.

An understanding of the modal features of base isolated structures assists in extending quantitative results to other structural and isolator systems and assists in estimating the significance of specific features of structures and their contents.