SEISMIC ISOLATORS FOR GROUND MOTIONS WITH LARGE DISPLACEMENTS AND VELOCITIES

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ABSTRACT

Well-damped flexible structures, or structures given these features by seismic isolation, are only moderately loaded by severe El Centro 1940 type earthquake motions, while undergoing acceptable levels of displacement. However at near-source sites severe earthquake motions often include a large and sustained acceleration pulse, and associated very large velocity and displacement pulses. Such near-source pulses substantially increase the loads and greatly increase the displacements of flexible and isolated structures which have been designed for El Centro 1940 - type earthquakes. If a bilinear isolation system is given a large ratio of yield-force to supported weight, say 0.15 to 0.25, then its displacements during earthquakes with severe near-source pulses, are substantially reduced and can be accommodated by appropriate isolator design. Severe loads are reduced to one, or a very few, pulses. However the degree of isolation during the relatively much more frequent earthquakes without a near-source pulse is much reduced by the large yield-force/weight ratio. If now the isolator is modified to have a moderate yield-force ratio for moderate displacements, and to give the effect of an increasing yield force, or hysteretic resistance, with increasing displacement, then effective isolation can be restored for earthquakes without near-source pulses, while retaining acceptable performance during the relatively rare earthquakes which give large near-source pulses at the given site. The paper describes some isolation systems which may give these results. Additional isolator features which may assist during large near-sources pulses include measures to reduce the deformations and damaging strains on laminated rubber bearings, and to support the building without destructive shocks if bearings loose their vertical load capacity.

KEYWORDS

seismic attack,; near-source pulses; extreme earthquakes; isolators; high displacement; high variable hysteresis; resilient buffers.

NEAR-SOURCE EARTHQUAKE MOTIONS

During the last 25 years, earlier assumptions about near-source ground motions during severe earthquakes have undergone serious revisions. Earlier it was commonly assumed that large fault fractures, at any location on the fault surface, occurred progressively during a substantial interval, say 10 to 15 seconds. Such a fracture action is consistent with "El Centro 1940 - type" ground motions. With the rapidly increasing number of strong-motion earthquake recorders since about 1960 a rather detailed picture of ground motions near rupturing faults is emerging.

A somewhat unexpected and hazardous feature of near-source ground motions, during earthquakes of moment magnitude, M_w , greater than 6.5 is the frequent occurrance of large displacement velocity and acceleration pulses, with unidirectional durations greater than 1.0 seconds. Near-source higher-frequency accelerations are also very large and may exceed 10 m s^{-2}. In a list of 27 such recorded ground motions by Heaton et al (1995), the earliest is Pacoima Dam, S 15°W, 1971. These severe motions were regarded as atypical at the time because of the extremely irregular topography. The second recording describing the damaging effects of such near-source ground motions include Bertero et al (1978) and Anderson and Bertero (1987).

At a given site in a high seismicity area the recurrence intervals for extreme earthquakes from rupture of a nearby fault will be very long. However the recurrence intervals for large earthquakes, due to extreme motions on more distant faults or to large but not extreme earthquakes on nearer faults, will be relatively short. Hence isolated structures should be designed for a good performance during moderate and severe earthquakes as well as for acceptable performance during an extreme earthquake with large near-source motion pulses.

The isolated 10-storey Wellington Central Police Station, intended to remain functional after a very severe earthquake, was designed in the mid 1980s. The Pacoima Dam, 1971, motions scaled by a factor of 0.8 were included among the design earthquakes, and isolator clearances were provided to accommodate the resulting displacements. A resilient buffer system was included to accommodate larger isolator displacement demands, greater than $\pm$ 375 mm (Skinner, Robinson and McVerry, 1993).

ISOLATOR PERFORMANCE AT NEAR-SOURCE LOCATIONS

During severe and extreme earthquakes the ground motions at near-source locations often include a sustained acceleration pulse, and associated large velocity and displacement pulses, which are additional to higher frequency El Centro 1940 type motions, ie motions with response spectra similar to those of the El Centro NS 1940 record. These large pulses cause a severe attack on flexible structures, and on structures made flexible by isolation systems. Isolated structures, with high-deformation periods in excess of 1.5 to 2.0 seconds, may be subject to very high ductility demands and high P-delta effects, particularly if deformations are concentrated towards the base of the structure, a result frequently enhanced by "non-structural' components. Typical isolated structures, and their contents, are subject to high lateral loads and to large displacement demands on the isolators. Such loads and displacements may be substantially reduced and accommodated by special isolator designs.

As a check on isolated-structure responses, at near-source sites during severe earthquakes, the ground motions recorded at Sylmar Hospital, 360°, 1994 (Darragh et al 1994), and the motions at Pacoima Dam, S 15° W, 1971 (Bertero et al, 1978), were applied to a simple 3-mass structural model, with and without bi-linear isolation. These structural models approximate those of classes (iv) and (i) in Section 2.5 of the authors' book, with an elastic period of 0.8 seconds and a yield "period" of 2.0 seconds, (loc. cit). It was found that an increase in the isolator yield force ratio, Q_y/W, from 0.05 to 0.25 caused the maximum isolator displacement for Sylmar Hospital motions to fall from 0.46 m to 0.19 m, and the displacement for Pacoima Dam motions to fall from 0.40 m to 0.28 m. In both cases the ratio of base shear force to supported mass remained in the range from about 4.5 to 5.0 ms^{-2}. Top mass accelerations were substantially increased by higher "mode" action at all yield levels for Sylmar Hospital motions, and at higher yield levels for Pacoima Dam motions. When the building viscous damping was increased from 5% to 20%, in an attempt to represent the effect of structural damping with a high ductility factor, top mass accelerations remained in the 4.5 to 5.0 ms^{-2} range. A more detailed analysis is required to check the extent of higher mode suppression by structural ductility. The higher yield force ratios were inappropriate for less severe earthquake motions. An increase from 0.05 to 0.15 caused an increase from 1.1 to 2.2 ms^{-2} in the a base shear/mass ratio for El Centro, NS 1940, motions.

Attempts have been made to derive typical near-source earthquake motions from fault-fracture models for earthquakes with $M_w = 7.0$ (Heaton et al 1995), with motions computed for a 60 km x 60 km area above and up-dip from a fault plane. They applied these derived motions to a 20 storey steel-frame building model and a 3 storey base-isolated building model. The lowest storey of the steel-frame building model suffered very severe deformations which were 6% of the storey height at 3 of the 144 grid locations, and deformations of over 2% of storey height at almost 30% of the grid locations.

The isolated building model used by Heaton et al, 1995, was similar to the above class (iv) model used by the authors. They adopted a yield-force ratio $Q_y/W = 0.09$. This gave hysteretic damping equivalent to 15% viscous damping at cyclic displacements of 0.40 m. Additional viscous damping of 10% was added to the isolators. With the derived earthquake motions for $M_w = 7.0$, this model gave an isolator displacement demand of about 0.66 m and a base shear/weight ratio of $S_b/W = 0.45$ at the most demanding locations. The authors' analysis using Sylmar Hospital and Pacoima Dam motions suggest that a substantially lower isolator displacement demand would have occurred if the isolator yield ratios had been increased from 0.09 to 0.20 or 0.30. However such large isolator yield ratios would result in somewhat ineffective isolation during relatively frequent moderate and severe earthquake motions which do not include large near-source pulses.

ISOLATORS MODIFIED TO IMPROVE PERFORMANCE

A number of isolation strategies may be adopted to provide acceptable performance during very infrequent extreme near-source ground motions, while retaining effective isolation during relatively frequent moderate and severe earthquake motions, which do not include large near-source pulses. Such isolators must provide for large displacements during extreme near-source earthquakes. The mounts must provide the displacements by some combination of elastic and plastic deformation and sliding. The isolator hysteretic and centering forces should be moderate during relatively moderate isolator displacements, to provide effective isolation during earthquakes which do not cause very large isolator deformations. However, the isolator hysteretic forces should rise to high values during large displacements, to substantially reduce the very large displacements. This might be achieved by double-acting elastoplastic buffers, with appropriate clearances, which give isolator-displacement loops of the form shown in Fig 1(a). A set of buffers might be given varying clearances to give a more gradual transition to high hysteretic forces. These hysteretic forces can be provided by the plastic deformation of steel or lead, or by frictional forces. The isolator force-displacement loops can then be idealized as in Fig 1(b). Such elastic and hysteretic forces may be arranged to provide near-optimum performance for a very wide range of isolator displacement.

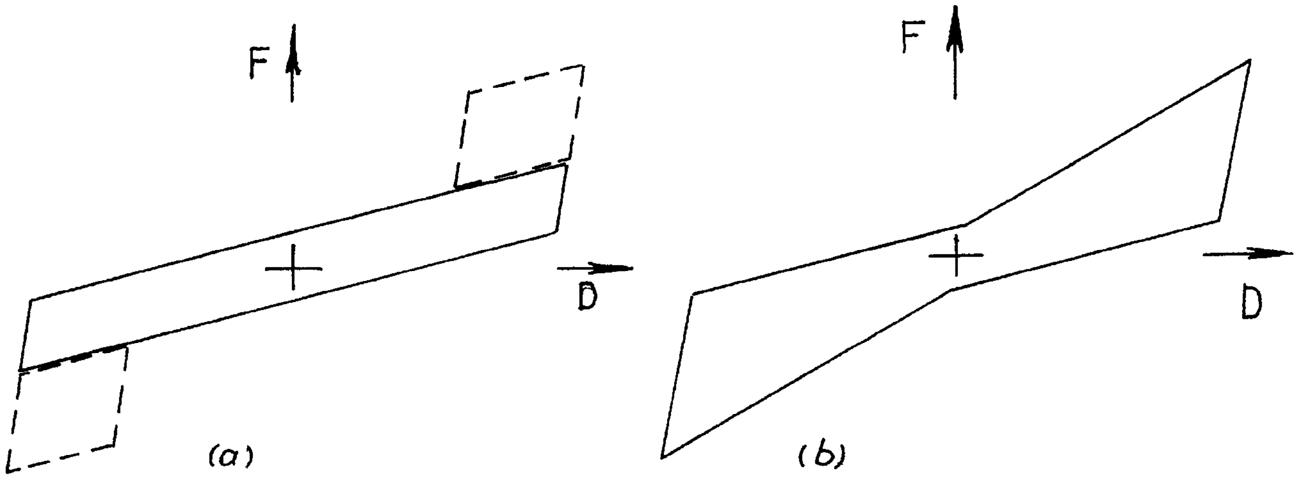

Fig 1. Hysteretic forces increased to reduce displacements during extreme and near-source earthquakes.
(a) Two-level hysteretic resistance (b) Varying hysteretic resistance

ISOLATORS FOR EXTREME NEAR-SOURCE MOTIONS

When an isolated structure may be subject to extreme near-source motions the favourable load-deflection features illustrated in Fig 1 may be approximated by selecting isolator components from a wide range of existing or readily developed devices.

Anchored Lead-Rubber Bearings

A well-anchored lead-rubber isolator mount can survive one or a few very large displacements despite considerable rubber damage, with little performance change during subsequent moderate displacements.

The rubber damage is caused primarily by negative pressures arising from large end movements on severely deformed bearings, unless the bearing diameter is large compared with the displacement. This rubber damage may be increased by the accompanying high shear strains. For a given bearing displacement negative pressures are reduced for increased bearing diameter, and shear strains are reduced by increased bearing height. Bearing shear stiffness remains unaltered if the bearing height is increased by the same fraction as the increase in plan area. Such oversize bearings can survive larger extreme displacements.

Extreme lead-rubber bearing deformation may also cause rubber and steel-lamination damage near the lead plug surface, which may give some reduction in hysteretic damping during moderate- displacement cycles.

Segmented Bearings for Large Displacements

While oversize bearings can give a substantial increase in survivable extreme isolator displacements, very large increases in displacement can be provided more efficiently by segmenting the bearing, as discussed in section 3.4.5 of the authors' book (loc.cit). The bearing is subdivided into 4 spaced columns, and column tilting is suppressed at several levels by horizontal stabilization plates across all four columns. The displacement capacity is increased by half the number of segments in each vertical column. Hence 5 stabilization plates, giving 6 segments per column, triples the acceptable displacement.

It is convenient if isolator hysteretic damping can be provided by means other than including lead plugs in the many segments of the above bearings.

Lead-Rubber Mounts With Sliding End Plates

A lead-rubber bearing may be provided with an end plate which slides, to provide increased displacements during very severe earthquakes, as shown in Fig. 2(a). The sliding friction modifies the load-deflection loop of the mount as shown dotted in Fig 2(b). The change in loop shape gives a large increase in effective period, for very large displacements. This considerably reduces displacement demands and mount shear forces. If the displacement demand exceeds that provided by the sliding surface, further deformation of the lead-rubber bearing adds the chain-dotted features to the load-deflection loop of Fig 2(b).

The area of siding surfaces can be reduced by providing slide channels at the top and bottom of lead-rubber bearing, with the channels at right angles to provide sliding in any horizontal direction. The bearing ends may be made captive in the channels to prevent end tilting due to bearing end movements.

To prevent progressive drift during repeated bearing sliding, a moderate fraction of the mounts in an isolator can be without a sliding feature. The non-sliding mounts can be given the required displacement capacity by segmentation as discussed earlier. A suitable coefficient of friction would usually lie in the range from 0.1 to 0.25.

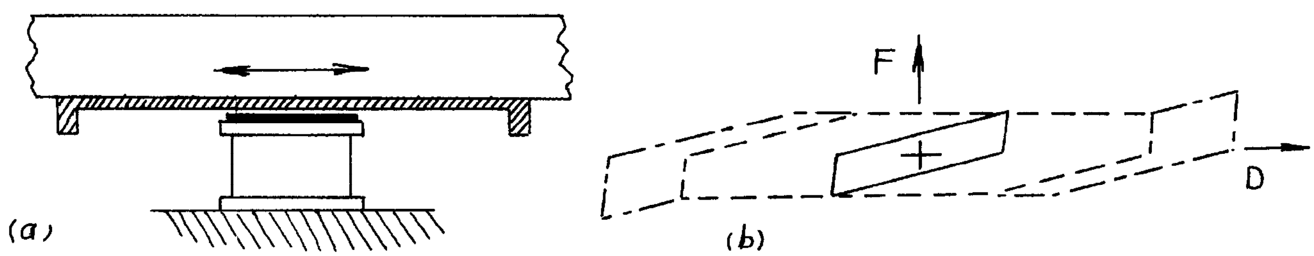

Fig 2,
(a) Laminated rubber bearing with sliding and slide stops
(b) Load-deflection loops:
solid line - without **sliding**
dotted line - sliding without stops
chain dotted line - with sliding and stops

Resilient Hysteretic Buffers

Double -acting hysteretic buffers may be included in isolation systems to provide the load-deflection features idealised by the loops given in Fig 1 above. A conceptually simple version of such a buffer is the tapered vertical steel beam shown in Fig 3, with an appropriate clearance to the cylindrical stop plate to allow unbuffered motions. This steel buffer provides both elastic and plastic resistance which may be idealized by the dotted bilinear additions to the loop of Fig 1(a). The size and shape of the buffer bilinear loop can be controlled by the beam dimensions, as discussed in Section 3.3. of the authors' book (loc. cit). The steel buffer can tolerate very high steel strains of 0.1 to 0.15 for the few very large deformations which may occur during an extreme earthquake.

For a particular isolation system a range of hysteretic buffers, with different clearances to stops and different load-deflection loops, may be used to approximate the form of isolator loop shown in Fig 1 (b), or other isolator loop shapes which may be better for particular applications. Alternatively the load-deflection loop of a particular steel-beam buffer may be modified by constraints of the form indicated by the dotted curves in Fig 3.

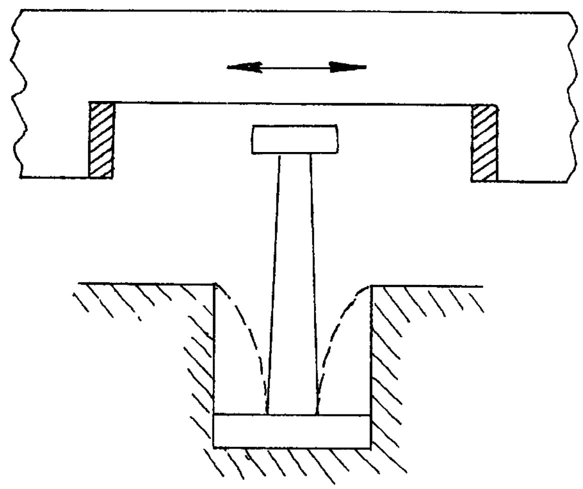

Fig. 3 Double-acting resilient hysteretic steel buffer.

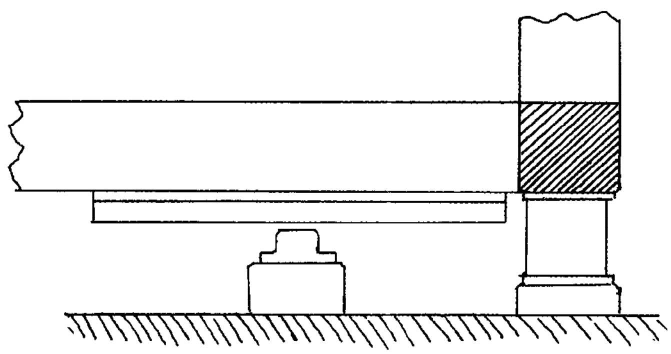

Fig. 4 Crossed-rail emergency building support.

Emergency Support and Large-Deformation Friction

Emergency building support may be provided by the crossed rails shown in Fig. 4. These would support the building in the event of the failure or excessive instability of a bearing. In principle the rail clearances and side profiles could be adjusted to give controlled frictional forces and reduced gravity loads on bearings during large isolator displacements. In practice, creep in the bearing height and foundation settlement may alter the rail clearances and deflected loading forces. Hence some checks should be made on rail clearances. Also such "controlled" friction should be confined to supports not too far from the vertical axis of the isolated building, to avoid excessive torsional unbalance of friction forces.

Steel-to-steel friction could be replaced by pad -to-steel friction by including pads in a cruciform carriage which is constrained to movement along both rails.

Many isolator components, including the sliding lead-rubber bearing, Fig. 2(a), and the crossed rail emergency supports, Fig. 4, require some further development and testing before being included in isolator systems. Moreover the performance of isolated structures, using the types of isolators suggested, should be established on the basis of detailed model analysis.

FURTHER DEVELOPMENTS

Severity, Frequency and Character of Severe Earthquake Motions

Further research will better delineate those locations for which it is necessary, and those locations for which it is not necessary, to consider provisions for large near-source pulses in aseismic design.

Of great interest and considerable concern is the severity and somewhat unexpected character of many near-source ground motions during severe and extreme earthquakes. While important progress has already been made in defining the site-specific severity, frequency and character of ground motions during moderate, severe (of El Centro 1940 level), and extreme earthquakes, much more remains to be done to ensure that appropriate measures against earthquake attack can be provided. Encouraging signs include the increasingly rapid progress being made in defining site-specific earthquake motions made possible by increases in the number and effectiveness of ground motion and deformation recording systems. Also encouraging is the increasingly effective modelling of the spatial distribution of ground motions for major earthquake events, made possible by recorded data, and by increasingly powerful and effective computing systems.

Developing Isolation Systems

This paper describes isolation systems which may provide a reasonable compromise between giving high isolation protection to structures and/or their contents during relatively frequent moderate and severe earthquake motions (of similar intensity and character to the north-south component of the 1940 El Centro accelerogram), while giving a high probability of acceptable performance during relatively rare extreme earthquake motions at near fault locations. A brief description is given of a few isolator components which should be capable of providing the desired isolator features. A wide range of further isolator components which have been described in the literature could well be adapted to give the above isolator features, or other isolator features found to be more appropriate for particular structural and contents vulnerabilities, and for particular earthquake motion hazards.

Further development will include the better definition of optimum isolator features and the further development of components which can provide the desired features economically. Another challenge is the development of isolation systems which can be readily adapted to meet changing perceptions of appropriate isolator features. Already a number of isolated structures can be retrofitted more readily to meet changed perceived needs than can their unisolated counterparts.

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