ROCKING STRUCTURE DESIGN CONSIDERATIONS

by

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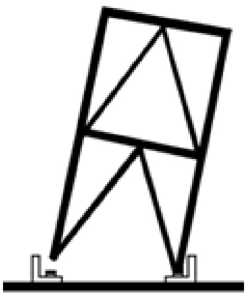
1. *Background*

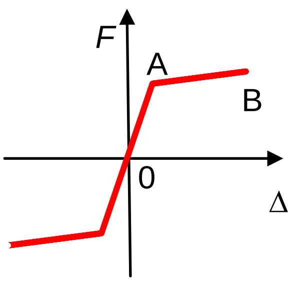
Rocking structures uplift under severe lateral seismic accelerations as shown in Figure 1a. The structures themselves maybe walls (e.g. steel shear walls) or stiff frames (e.g. CBF) which are expected to remain elastic.

The deformation is in several stages under lateral force as shown in Figure 1b:

i) 0-A. Elastic deformation of the frame before uplift of one side of the frame/wall occurs at A.
ii) A-B. Increased deformation after uplift has occurred at a lower rate of increase in force. As the displacement increases, the uplift increases, causing greater gaps at the bottom of the frame.
iii) B-A. After reaching the peak displacement, the structure the structure returns along the same loading curve.
iv) At A there is an increase in stiffness when the gap at the structure disappears. This is usually associated with impact as the structure is likely to be moving at a significant velocity at this time.
v) A-0. There is elastic unloading and the structure may then deform and uplift in the opposite direction.



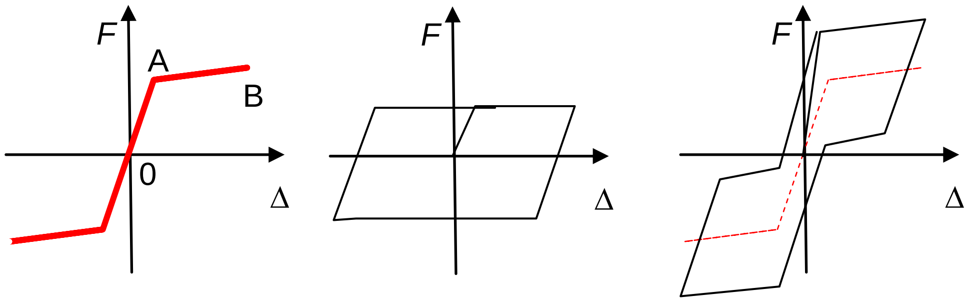
(a) Frame (Chanchi et al. 2010)



(b) Rocking - no dissipaters

Figure 1. Rocking Behaviour of Steel Structure

The presence of an elastic perfectly plastic (EPP) dissipater changes the hysteresis loop to that in Figure 2. It may be seen that the dissipater increases the initial stiffness. It also means that there will be no static self-centring since there will be displacement when the force is zero. However, dynamic self centring may occur as a result of inertial effects (MacRae and Kawashima, 1997).



(a) Rocking (b) Dissipation (c) Combined

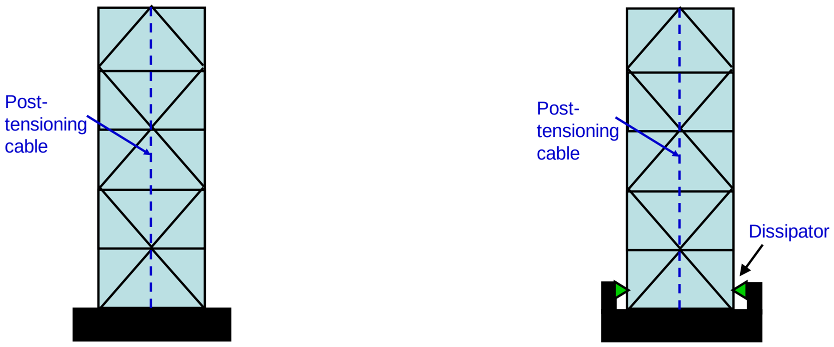
Figure 2. Rocking Behaviour of Structure with Dissipaters (Chanchi et al. 2010)

New Zealand designers have a legacy of designing rocking structures, as shown from the 1981 South Rangitikei Rail Bridge, a world leading application of rocking solutions to bridge piers. Specific rocking studies of elevated freeway bridges was conducted by Xiao et al. (1992). The first steel structure designed to rock was built in Wellington in 2007 (Gledhill et al. 2008), idealized in Figure 1. Here the self-centring cables are attached to springs at the bottom of the legs in Figure 2b. These springs increase the level of earthquake inertia force under which uplift occurs, thereby increasing the secant stiffness and reducing the expected frame displacements.

(a) Schematic (b) Photo of Springs in the Legs (Sidwell, 2010)

Figure 2. Rocking Structure in Wellington

Recently other rocking systems have been proposed and testing has been conducted by groups based at i) Lehigh (Roke et al. 2009) and ii) Stanford-Illinois-TIT (Deierlein et al. 2010) as shown in Figure 3. The Stanford-Illinois-TIT frame costs more because of the dissipater, and the dissipater reduces the response. Here, post-tensioned cables extend to the top of the structures. This results in larger member sizes throughout the frame than in the NZ approach, but it obviates the need for the springs.



(a) Lehigh Proposal (Sause et al. 2010) (b) Stanford et al. Proposal (Deierlein et al. 2010)
Figure 3. Different Configurations for Rocking Structures

The desirable characteristics of rocking structures are that they:
a) May be stiff, reducing peak displacements
b) Have low damage
c) Have low permanent displacements
d) There are no foundation tension demands

This paper describes a number of issues that should be addressed for appropriate design.

2. *Design Considerations*

A number of issues with rocking structures have not been fully addressed (MacRae 2010, MacRae and Clifton, 2012) include:

a) Providing Rocking Frame Resistance Against Uplift

   Restoring forces from the following sources prevent uplift:
   a) gravity accelerations acting on the frame,
   b) post-tension force, provided by
      a. springs, or
      b. post-tensioning cables.

   Uplift, which is affected by the gravity accelerations and the post-tensioning force should be prevented under wind conditions.

   Recommendation:
   Restoring forces from gravity and post-tensioning should be sufficient to prevent uplift due to wind actions and under the serviceability limit state earthquake.

b) Providing Rocking Frame Seismic Strength

   Restoring forces are from:
   c) gravity accelerations acting on the frame,
   d) post-tension force (optional), provided by
      a. springs, or
      b. post-tensioning cables.
   e) elastic deformation of the slab/gravity frame (optional)
   f) dissipaters (optional)

These restoring forces must be sufficient to resist the design level earthquake forces for serviceability and ultimate (DBE) limit states. Current codes do not specify R (or k_μ) values for rocking frames, but those for the appropriate wall/frame material/configuration should be used until further studies considering stability, P-delta effects etc, have been completed. In reality, one of the factors affecting the ductility capacity is the strain in the post-tensioning devices.

Recommendation:

Restoring forces from all sources should be sufficient to resist the required lateral forces from earthquake.

c) Use of Dissipaters

Dissipaters are activated once uplift starts.

Dissipaters may be:

a) Yielding devices
b) Friction devices
c) Viscous devices
d) Other special devices (such as lead dissipaters)

Dissipaters can:

i) Increase the lateral force resistance of the frame. This can result in reduced peak displacements.
ii) Increase the energy dissipation, possibly reducing the lateral displacements and vertical impact forces.
iii) Increase the permanent displacements of the frame (except viscous dissipaters).

If large dissipaters are used, then residual displacements may be large. These may be removed after the earthquake by removal/replacement of the dissipaters. For example, for a friction dissipater, this could be accomplished by untightening and retightening the bolts.

Dynamic stability considerations (MacRae and Kawashima et al. 1997) may also be used to limit permanent displacements. They are likely to be low if the dissipater force is less than the uplift restoring force from gravity and post-tensioning.

Recommendation:

The maximum dissipater force should be less than the restoring force provided by gravity and the post-tensioning at uplift.

d) Horizontal accelerations resulting from the impact

Large horizontal accelerations affecting building elements, attachments, people and contents can occur. These can occur in all "clickety-clack" systems. These are systems with a rapid increase in stiffness when the structure is travelling at high velocity. Such buildings include those with traditional (buckling) concentric braces with medium to high slenderness ratios, pure steel plate shear walls, post-tensioned beams, rocking structures, concrete walls and others. This issue was first raised by MacRae (2010) where a motorbike was shown travelling at constant velocity. Because it is at constant velocity, the horizontal forces and accelerations on the motorcyclist are zero. However, the when the motorbike suddenly hits a wall, the forces on the bike suddenly increase, until the wall is pushed over. This is illustrated in Figure 4. The hysteresis loop for the motorcycle in Figure 4b is similar to that for many clickety-clack structures. The following provocative question was raised: "Is the difference between the motorcyclist, and a person in a "clickety-clack" building during an earthquake, only the amount of protection they are wearing?". Anecdotal evidence (e.g. Bull 2011, Clifton 2011) indicates that in buildings of this type, including concrete shearwall buildings, due to the high increase in stiffness at high velocity, many items and people were thrown across rooms during the 22 February 2011 Christchurch earthquake. This is similar to the way the motorcyclist may be expected to be thrown of their motorcycle.

(a) Motorbike and Wall (b) Hysteresis Curve

Figure 4. Hysteresis for Sudden Stiffness Change at High Velocity (WWW, 2010)

Research (e.g. Lin et al. 2012) has shown that for non-linear systems with the same envelope hysteresis curve, higher contents displacement sliding demands occur for those curves which result in higher during unloading.

Recommendation:

To avoid severe sliding displacements, the contents should be anchored to the structure following the standard code process.

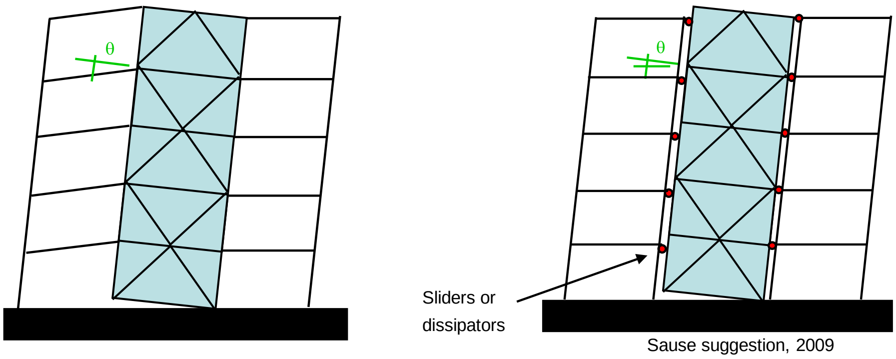
e) Frame/slab demands due to vertical uplift deformations

Vertical deformations on the side of the frame may result in large demands to the floor slab as it needs to kink through the angle θ in Figure 5a. This interaction with the rest of the frame may limit the rocking that occurs, and it may cause damage in the frame. Several approaches have been suggested (MacRae, 2010, 2011). These include:

a. Allowing the floor to rip. Apparently this is acceptable to some Californian engineering companies (Deierlein, 2010), but it means that the structure sustains damage, and this defeats one of the major goals of rocking structures.
b. The gravity columns could be placed a significant distance away from the rocking frame so they are not subject to significant tension, and the floor slab could be made thin enough that it can undergo the expected displacements almost elastically. Calculations would be required to ensure that this can be done. Initial studies on this (Clifton, 2013) indicate the

elastic out of plane capacity of the floor slab is significant irrespective of the span, as the floor slab out of plane stiffness increases as the span increases.

c. Sause et al. (2010) proposed separating the rocking frame from the rest of the structure as shown in Figure 5b. Here, dissipaters between the frame and the rest of the structure may be placed to dissipate energy. Horizontal plates between the rocking frame and the structure behind may be use to transfer lateral forces, but not forces due to relative vertical deformation, as shown in Figure 6. The horizontal plate does not have much resistance resisting vertical load, but it does resist the horizontal load.



(a) Deformation if Attached to Frame (b) Separation of Frames

Figure 5. Rocking Frame – Gravity Frame Interaction

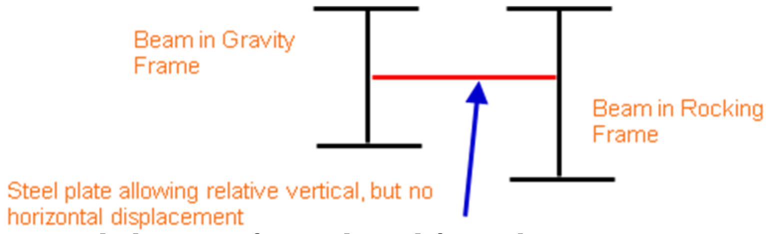


Figure 6. Horizontal plate transferring lateral forces between gravity and seismic frames

Recommendation:

Specific allowance must be made for vertical uplift to ensure that the slab is not damaged.

f) Rocking structure shear and moment demands

The moment demand at the base of a rocking structure is limited by the flexural capacity at the base. However, dynamic effects in earthquake loading may mean that the shear forces and the distribution of moments over the height of the rocking structure may be significantly different from that calculated based on first mode response of a rigid rocking mechanism. Distributions of shears and moments depend on the magnitude and frequency components of earthquake shaking as well as the structural characteristics. While research is on-going around the world to better assess these demands, in the intermediate term the design information in the commentary to the NZ concrete code (NZS3101, 1995) can be used. More current information is available by Priestley et al. (2002) using shear and moment dynamic magnification factors.

Recommendation:

The design should ensure that the flexural and shear resistance of the rocking wall is sufficient over it's height.

g) Gravity frame demands

It is necessary to design the gravity frame for the expected demands too. If the frame is fully pinned, then the demands due to lateral deformations are not significant and can be ignored. However, special detailing care is needed in the locations where the frame may uplift.

Recommendation:
The design should ensure that the resistance of gravity frames is sufficient over its height.

h) Non-structural elements

Non-structural elements which are part of buildings should be designed to resist the accelerations, and to not suffer as a result of deformations which may occur. Methods for doing this are available (MacRae et al., 2012).

Recommendation:
Non-structural elements should not be damaged during the design level shaking event.

i) Magnitude of Vertical Impact Accelerations

Vertical accelerations result from impact on the foundation as the frame returns to its initial position. Restrepo (2010) indicated vertical accelerations as great as 4g in a concrete rocking wall in a recent test. These vertical accelerations will affect the non-structural elements, such as the ceiling tiles, as well as contents and occupants. The impact forces are likely to occur when the frame is at zero displacement, so it is out-of-phase with the maximum forces expected in the frame. Because of this, they may not have significant effects on the frame itself, but further studies are required to understand the likely effects especially on non-structural elements given the short duration, in conjunction with the high pulse accelerations.

Vertical impact accelerations may also be influenced by vertical ground accelerations however Singh et al. (2009) has shown that these effects are generally small.

Recommendation:
Vertical impact accelerations should be ignored and vertical ground accelerations are likely to be small.

Conclusions

Rocking structures can be used in low damage building construction. Their lateral strength is provided by a combination of gravity load effects, post-tensioning, gravity frame elastic effects and dissipaters. Without dissipaters they have statically self-centring characteristics. With dissipaters, they are likely to have small residual displacement displacements if the dissipater force is low. If the dissipater force is high, residual displacements may be removed by removing the dissipater attachment. Dynamic magnification effects need to be considered of the rocking wall/frame is to remain elastic. Displacement compatibility needs to be considered to ensure no damage to the slab or to the rest of the building. More care is required when fastening non-structural components than in traditional yielding structures. Recommendations for these key features are included in the paper. Well-designed rocking structures may behave very well in an earthquake as long as care is taken with the points discussed above.

Acknowledgements

Parts of this paper are taken from MacRae (2010).

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