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DYNAMICALLY STRAIGHTENING OF LOW-DAMAGE STEEL BUILDINGS AFTER EARTHQUAKE

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Abstract:

The residual interstory drift ratio (RISDR) of a three story 2-D steel frame building structure is studied under the same ground motions records applied twice. The records were chosen such that during the first shake the residual drift was close to 1%. Before the second shake the building is fitted with tension-only braces to encourage dynamic re-straightening. The tension-only braces are steel rods which yield in tension and carry no force in compression. It is shown that increasing the story strength of the structure by adding tension-only braces can straighten the structure. However, over-straightening may also occur causing significant residual drifts in the opposite direction. Increasing brace stiffness while maintaining the same strength causes the residual interstory drift ratio (RISDR) of the structure to first decrease and then increase slightly. At high brace stiffnesses the RISDR becomes almost constant and independent of stiffness. For the particular case studied, the optimal increase of story strength and stiffness was 35% and 10% respectively for the shaking considered. With the addition of a brace with these characteristics, instead of the second shake approximately doubling the residual displacement, it reduces by about 100%, effectively straightening the structure.

Keywords: Effect of subsequent shakes; Dynamically re-straightening; Tension braces; Story strength and stiffness increase

1. Introduction

Major seismic events, such as the Canterbury earthquakes, have shown that buildings designed to modern code provisions may still require extensive repair or replacement due to receiving substantial damage. Also, recently, a number of techniques have been developed to minimize structural damage, such as the use of friction connections and energy dissipaters. However, there may be out-of-straightness as a result of post-earthquake residual deformations, which may detrimentally affect structure performance in subsequent seismic events.

There are contrary arguments about whether or not a number of earthquake shakes causes increased residual displacement demands. For example, Rad et al. (2015) [1] have shown that undamaged buildings constructed with initial permanent displacements tend to have increased peak and residual displacement demands in the initial displacement direction due to earthquake shaking. Moreover, analyses of buildings under September 2010 and February 2011 excitations of the Canterbury Earthquake Sequence [2] showed that residual inter-story drift response of the buildings is also increased in subsequent earthquake events. For example, the February event produced larger residual drifts after the September earthquake than when the February event was been applied alone.

However, observations from past earthquakes have shown that residual displacements can decrease with each subsequent shake in the earthquake sequence. For example, the residual roof displacement of Pacific Tower in Christchurch in Canterbury as shown in Figure 1 decreased from 60mm after the 2010 September event to 30mm after the 2011 February event [3].

Buildings are generally designed for only one design level earthquake event. If, during an aftershock, or subsequent earthquake, they experience increased displacements, they may collapse and destroy other buildings in their shadow. Such was a concern with the 43m tall Gallery Apartments which were demolished. They stood beside the Christchurch art gallery that became the civil defence headquarters following the Christchurch earthquakes. No study is known to have been performed to discourage buildings from having further displacements in the same direction during aftershocks which could possibly lead to collapse.

It may be seen from the above discussion that there is a need to develop methods to discourage buildings from having increased displacements during aftershocks.

Figure 1: Pacific Tower in Christchurch in Canterbury[4]

In order to address this need this paper uses inelastic dynamic time history analyses of a 3 story steel frame building using a suite of ground motion records to answer to the following questions:

1. How can tension brace strength affect the residual deformation of the buildings during aftershocks?
2. How can tension brace stiffness affect the residual deformation of the buildings during aftershocks?

2. Modelling and evaluation approach

A three-story steel building was selected in this investigation. The basic structure has floor masses of 20 tonnes and floor heights of 3m. Detailed information about member sizes and story strength and stiffness of the structure are also provided in **Table 1**. The fundamental period of the structure was 1.5s. Story stiffness and strength of the structure were calculated based on pushover analyses of the structure. Forces were applied at each floor and each storey stiffness was found from the storey shear obtained from the applied forces only (without the P-delta contribution) divided by the storey displacement which included P-delta effects. Such pushover curves as shown in **Figure 2** where the slope of the linear part of the push-over curve at each floor indicates the story stiffness at each floor. Here the yield drift ($\boldsymbol{Drift_y}$) is about 1.7% and yield forces ($\boldsymbol{F_y}$) of the structure at first, second and third floor are 103, 85.5 and 51kN respectively. It shows that for a peak roof drift of 3.2%, the roof ductility, μ, computed as the ratio of peak drift to yield drift, is about 1.9.

Table 1: Details of 3 Story Frame Elements

FLOOR	BEAMS	COLUMNS	Story Stiffness (kN/m)	Story Strength (kN)
3	**150UB 18**	**310WC 158**	**1020**	**51**
2	**200UB 29.8**	**310WC 158**	**1706**	**85.3**
1	**275PB 50**	**310WC 158**	**2060**	**103**

Based on the equal displacement assumption, d_u, the peak displacement of structure, is equal to $\mu.d_y$ where μ is the structure ductility and d_y is the yield displacement. The maximum possible residual displacement, d_r, for an elastically perfectly plastic hysteresis loop and no P-delta effects is d_u-d_y. Therefore, the ratio of maximum possible residual displacement to peak displacement is $(\mu-1)/\mu$ [1] which equals to (1.9-1)/1.9=0.47 for the current selected structure with a 3.2% peak roof drift since the ductility is 1.9 as described above.

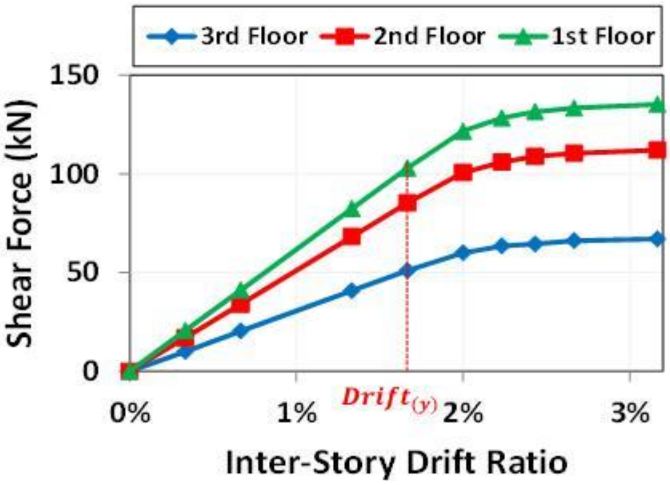


Figure 2: Push-Over Curve of the Structure

Simple steel rods were used as a tension-only brace. They were assumed to be reinforcing bars with diameters of 2, 3, 4.5, 6.5, 8, 9, 10, 12, and 13mm and yield strengths of 1.55, 3.5, 8, 16.5, 25, 32, 40, 56, 65kN respectively. They are placed in the structure after the first shake and before the second shake. This will cause the rod to be in more tension if the structure moves further in the direction it has already deformed, as shown in Figure 3b. The average increase of stiffness and strength over the height from the addition of the steel rods is shown in Table 2.

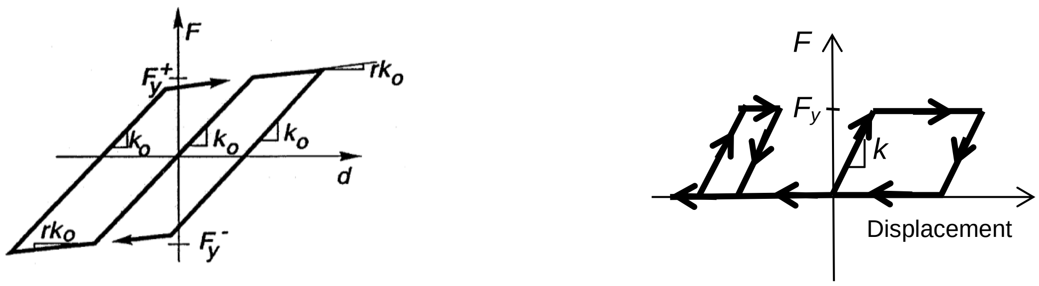
Table 2: Details of Steel Rod Tension Braces

Diameter of Steel Rod (mm)	**Increase of Story Stiffness (δ_k)**	**Increase of Story Strength(kN) (δ_s)**
2	**5%**	**2%**
3	**10%**	**4%**
4.5	**25%**	**9%**
6.5	**50%**	**18%**
8	**75%**	**27%**
9	**100%**	**35%**
10	**120%**	**42%**
11	**145%**	**52%**
12	**170%**	**62%**
13	**200%**	**75%**


(a) Steel Frame Building **(b) Out-of-straight Building with tension-only braces**

Figure 3: Structure Models

Bi-linear hysteresis loops with a post-elastic force-displacement stiffness factor of 1% were used for the flexural behaviour of the beam and columns as shown in Figure 4a. The tension only yielding brace elastoplastic hysteresis loop is shown in Figure 4b. Rayleigh damping equal to 5% of the critical value was assigned to the first and third modes and P-delta effects were considered.



(a) Bi-linear Hysteretic loop (b) Tension-only Elastoplastic Hysteretic loop

Figure 4: Hysteretic models

The SAC (SEAOCATC- CUREE) [5] suite of 20 earthquake ground motion records for Los Angeles with a probability of exceedance of 10% in 50 years were used. All earthquake records are scaled to get about +1% maximum residual drift and about +3% maximum peak drift over the height of the structure as shown in Table 3. The actual median residual and peak drifts obtained under the 20 records are 1.1% and 3.2% respectively. The second shake was the same as the first shake. It was applied in the same direction to insure that residual drift is increased. This is not meant to represent an actual aftershock, but it provides a tendency for the structure to continue moving in the same direction that can be mitigated by providing braces.

Dynamic inelastic time history was performed on OpenSees [6]. The structural strength was modelled using fiber sections. MATLAB [7] was used to extract the residual inter-story drift response (RISDR) of each storey. This is the residual relative displacement between floors above and below the storey considered normalized by the storey height. The peak RISDR ratio was chosen to be the maximum obtained from all stories. After the first shake was applied, tension-only braces may be applied before applying the second shake.

Table 3: Ground Motions Used

SAC Name	Record	Scale Factor	Residual Drift (%)	Peak Drift (%)
LA01	Imperial Valley, 1940, El Centro	0.8	1.18%	2.88%
LA02	Imperial Valley, 1940, El Centro	0.95	1.08%	2.94%
LA03	Imperial Valley, 1979, Array #05	0.75	1.10%	2.93%
LA04	Imperial Valley, 1979, Array #05	1.3	1.04%	2.80%
LA05	Imperial Valley, 1979, Array #06	-1.2	1.14%	3.32%
LA06	Imperial Valley, 1979, Array #06	1.6	1.16%	3.41%
LA07	Landers, 1992, Barstow	-1.0	1.18%	3.30%
LA08	Landers, 1992, Barstow	-0.8	1.07%	2.75%
LA09	Landers, 1992, Yermo	-0.5	1.09%	3.10%
LA10	Landers, 1992, Yermo	-0.7	1.02%	2.90%
LA11	Loma Prieta, 1989, Gilroy	-0.47	1.13%	3.09%
LA12	Loma Prieta, 1989, Gilroy	-2.4	0.9%	4.70%
LA13	Northridge, 1994, Newhall	-0.7	1.14%	3.29%

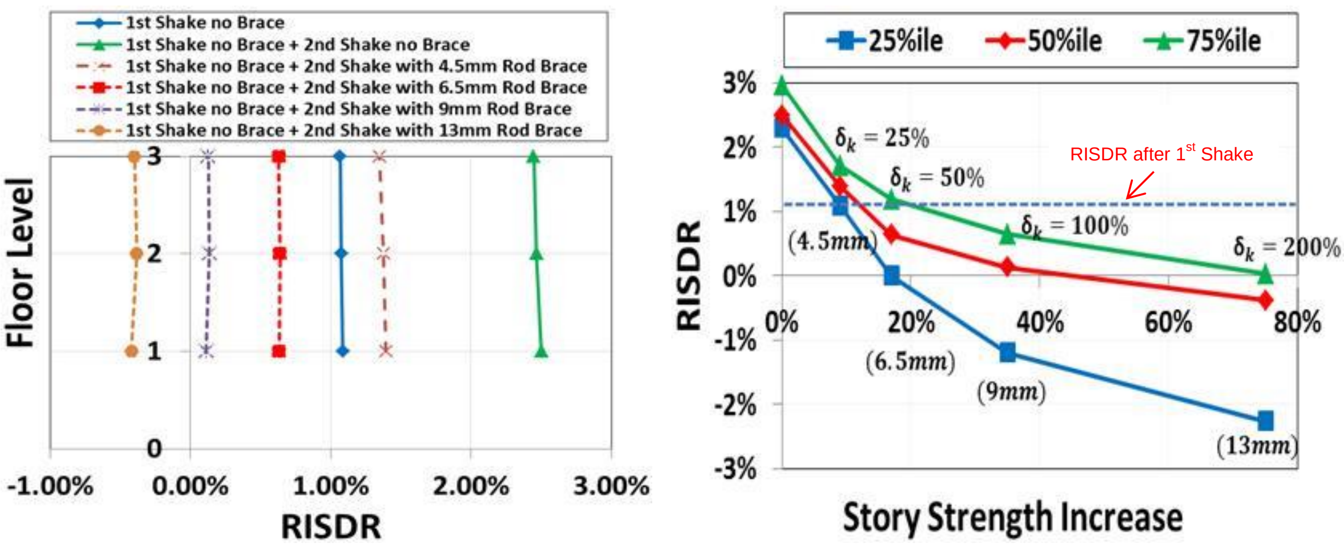
Table 3 continued

SAC Name	Record	Scale Factor	Residual Drift (%)	Peak Drift (%)
LA14	Northridge, 1994, Newhall	-0.87	1.07%	3.71%
LA15	Northridge, 1994, Rinaldi RS	0.7	1.09%	2.66%
LA16	Northridge, 1994, Rinaldi RS	0.45	1.00%	2.70%
LA17	Northridge, 1994, Sylmar	0.65	1.21%	2.99%
LA18	Northridge, 1994, Sylmar	-1.0	1.07%	4.5%
LA19	North Palm Springs, 1986	1.6	1.17%	3.41%
LA20	North Palm Springs, 1986	-1.00	0.7%	4.00 %

3. Effect of Stiffness and Strength Coupled

For a SDOF elastoplastic oscillator with no P-delta effect, the displacement obtained from applying the same ground motion twice in a row in the same direction would be expected to be exactly twice that from the ground motion applied once [8]. Even for this structure, with P-delta effects acting, residual displacements are approximately doubled as shown in Figure 5a. The figure also shows that the drifts at all levels are similar so the structural displacement response is governed by the first mode.

When tension braces are applied at all levels of the seismic frames between the two shakes, the building residual drift response, rather than increasing by more than two times in one direction, often reduce significantly. As the brace strength increases, the residual displacement from the second shake is in the opposite direction from that in the first shake. However, when the brace size is high, it can cause residual displacements in the opposite direction from that in the first shake. Figure 5b also compares the 25%, 50% and 75% percentile response of the RISDR of the structure considering different brace sizes also showing that larger tension braces reduce the RISDR in the primary direction.

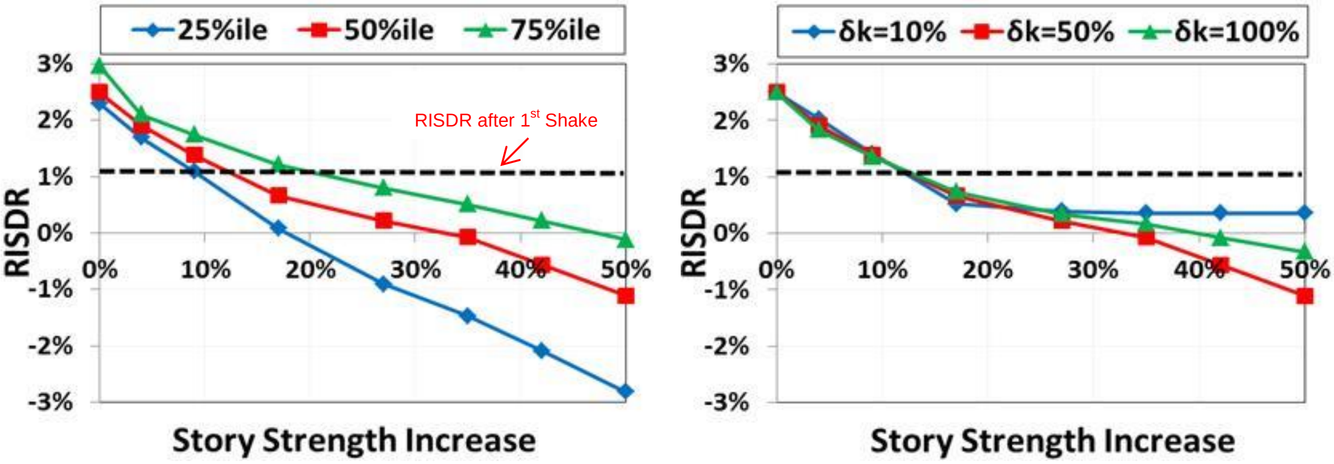


(a) 50%ile of RISDR (b) Maximum 25%, 50% and 75% of RISDR

Figure 5: Median RISDR of 3 story building

4. Effect of Strength only

Figure 6 shows the effect of increasing the structure story strength between the two events on the RISDR of the 3 story structure. Figure 6a compares the 25%, 50% and 75% percentile of the RISDR of the structure with each other by increasing the story strength of the structure. It indicates that by keeping the stiffness constant (δ_k = 50%) and increasing the strength of the tension brace, the RISDR of the structure decreases and it pushes the structure to move in the reverse direction. It also shows that by increasing 35% of story strength of the structure, the median RISDR of the structure becomes zero and makes the structure straight. Here, the negative RISDR means the structure become out-of-straight from other direction. Figure 6b compares the 50% percentile of the RISDR of the structure with different story stiffness. It shows that up to a story strength increase of 30%, the story stiffness did not have much effect. However, for greater story strength increases, there is variation if RISDR with stiffness, but no clear trend of RISDR with stiffness.



(a) δ_k = 50% (b) 50%ile of RISDR with different δ_k

Figure 6: Effect of Increasing Story Strength on Changing of RISDR

Decreasing RISDR with increasing strength alone can be explained based on the dynamic stability studies of MacRae [8] and Yeow et al. [9]. If F_y^+ is the yield strength in the positive direction, F_y^- is absolute value of the yield strength in negative direction, F_b is the added brace force, and A is the residual displacement of the structure after 1st shake. By making the structure becomes stronger in the positive direction, when the structure starts again to oscillate under the 2nd shake, it has a tendency to move in the weak direction. In this study F_y^+ and F_y^- are equal and since the ratio of $\frac{F_y^+ + F_b}{F_y^-}$ is greater than 1, so the building will have a tendency to yield in the negative direction and makes the structure straighten.

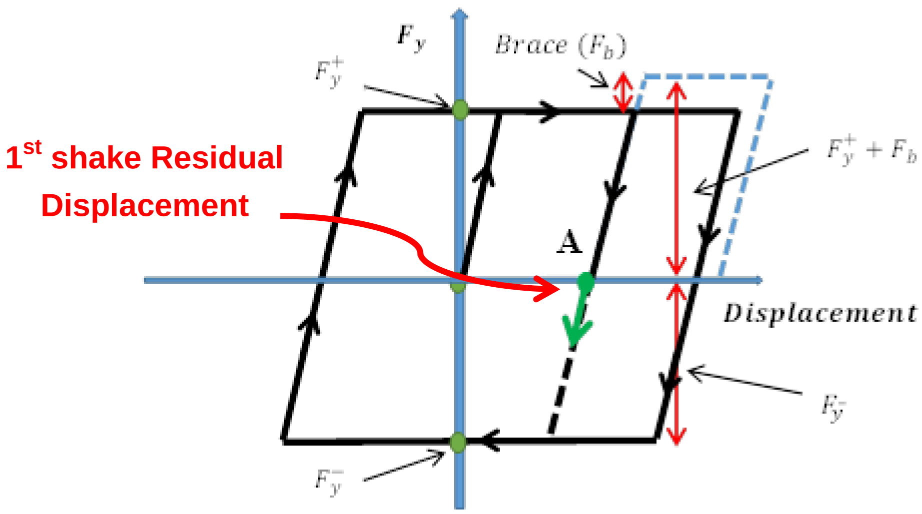


Figure 7: Hysteresis loop of the structure (Strength only increases)

When stiffness and strength are increased together, such as happens when adding a brace, the energy required to move from the zero force line to the point of first yield changes. If the strength increase is similar to the stiffness increase, then the yield displacement would be the same for both directions. However, the energy required to yield in the positive direction (green area) would be equal to the strength multiplier times that in the weaker direction (the yellow area). This would indicate that there would be a greater tendency for yield in the weaker direction if the oscillator were to vibrate freely. However, in the stiff direction, the structural period, and hence the the spectral displacement, is less indicating a greater likelihood of yield in the opposite (i.e. stronger) direction.

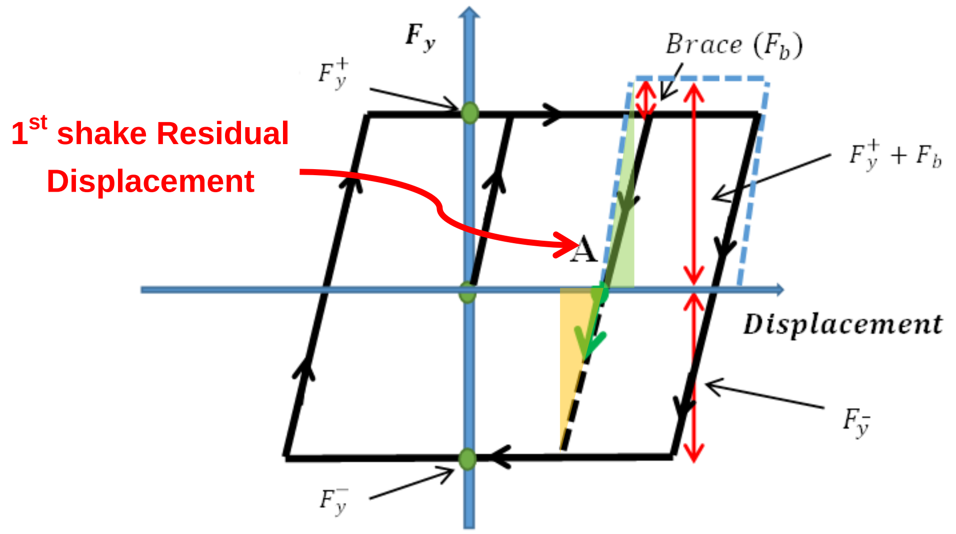


Figure 8: Hysteresis loop of the structure (Stiffness and Strength increase)

Figure 9 shows the effect of increasing strength in drift-time format for the Imperial Valley record (LA4). It shows that by increasing of the story strength after 1st shake, the RISDR of the structure decreases under the 2nd shake, but over strengthening may cause residual drifts in the opposite direction.

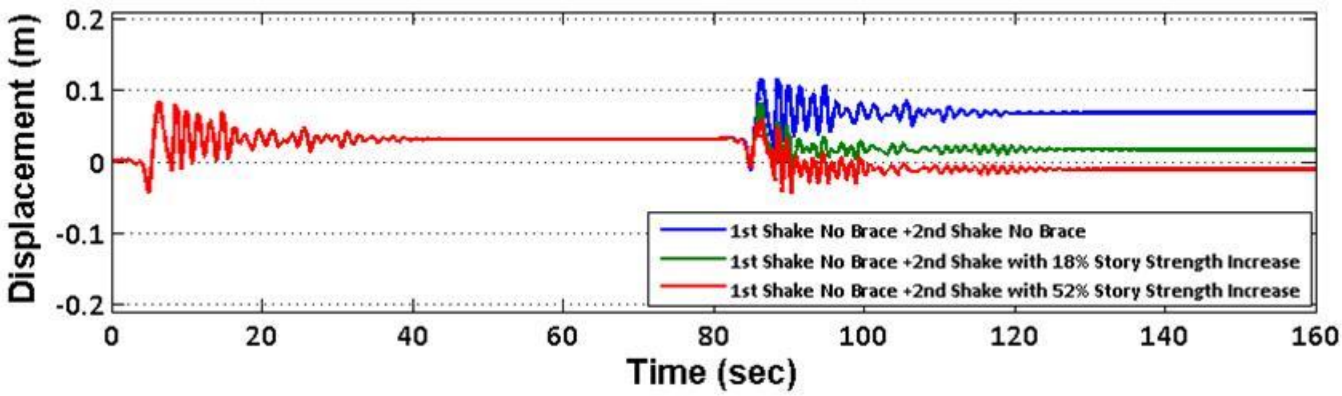
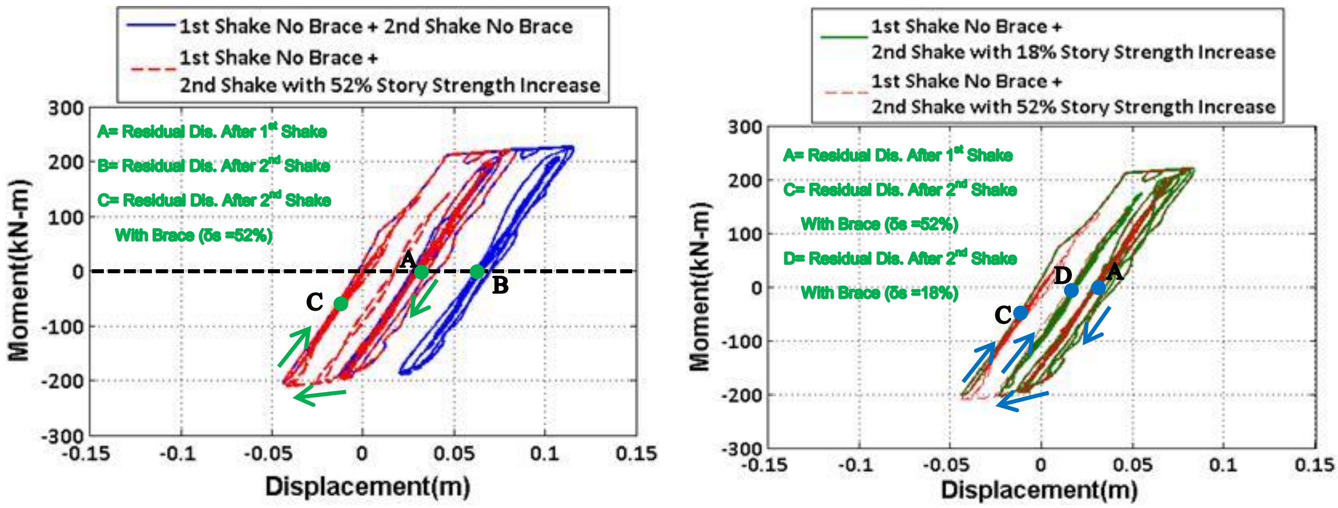


Figure 9: Effect of increasing story strength after 1st shake on 1st floor displacement response of the structure under 2nd shake for the Imperial Valley record (LA4).

Figure 10 shows a moment-displacement hysteresis curve of first floor beam of the 3 story structure. Figure 10a indicates that by applying the same ground motion twice in a row in the same direction, the structure tended to yield only in one direction. However, by increasing of the story strength (δ_S = 52%) after 1st shake, the building tended to yield in the negative direction and the RISDR of the structure decreased under the 2nd shake. Figure 10b also shows that by increasing the story strength from 18% to 52% the residual displacement of the structure tended to decreased more.



(a) δ_s =52%

(a) δ_s =18% & 52%

Figure 10: Moment-displacement hysteresis curve of first floor beam under the Imperial Valley record (LA4).

5. Effect of Stiffness Only

Figure 11a indicates that by keeping the story strength constant (δ_S = 18%), and increasing the story stiffness up to 10%, the RISDR decreases. For higher stiffnesses, the RISDR starts to increase and then becomes constant. The optimal increase of the story stiffness here is about 10%. Also, Figure 11b shows similar trends. When the strength increase is 42%, the RISDR becomes zero for high stiffnesses.

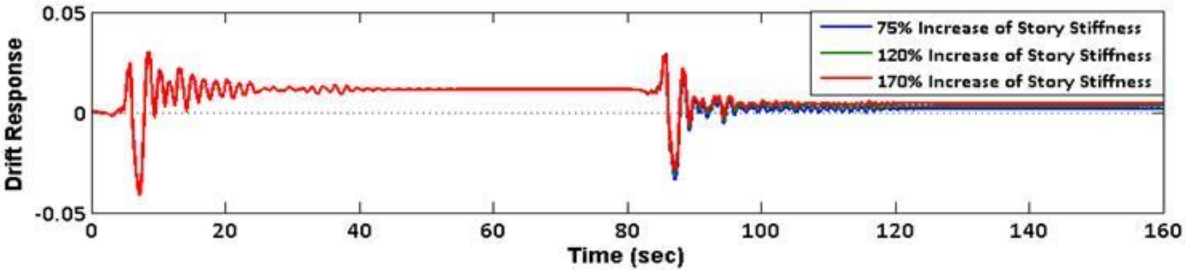
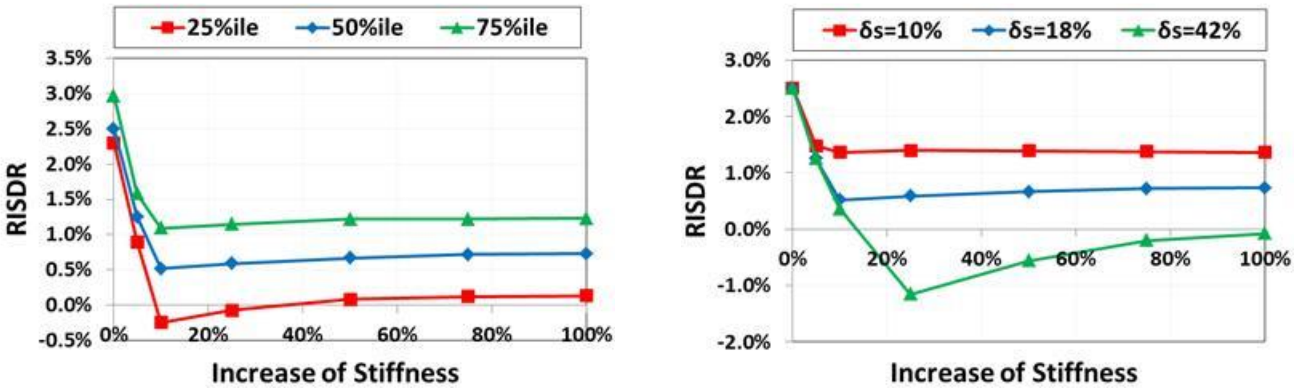


Figure 12 shows the information of Figure 11a in a drift-time format for the Northridge record (LA14). Here, by keeping the story strength constant (δ_S = 18%), the RISDR is not sensitive to the change in stiffness.



(a) δ_S = 17%

(b) 50%ile of RISDR with different δ_S

Figure 11: Effect of Stiffness of tension braces (δ_S = 18%) on changing of RISDR.

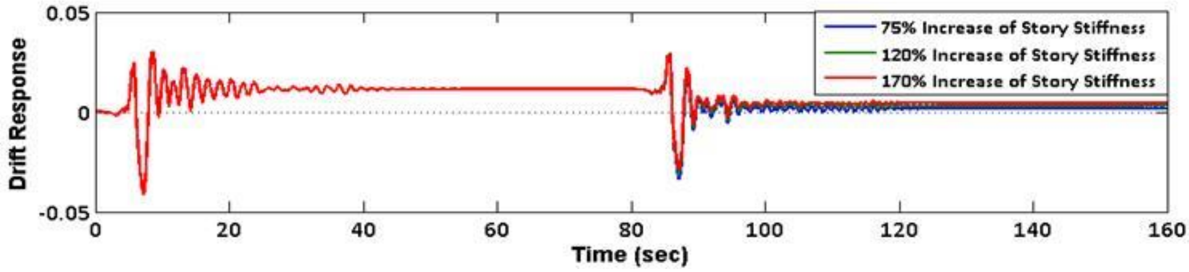


Figure 12: Effect of Increasing Story Stiffness (δ_S = 18%) on Roof Drift Response of the Structure for the Northridge Record (LA5).

6. Discussion

The studies above have shown that after the first shake, by increasing the story strength of the structure, the residual drift of the structure under 2nd shake decreases. This was expected based on energy method which was explained a little earlier, but is explained again below. Here, if a structure is pulled to the yield displacement in the positive direction and let go, and if damping is small, then the potential energy released is that beneath the hysteresis curve. When the oscillator reaches zero force, the potential energy is translated into kinetic energy and the oscillator has velocity. It therefore does not tend to stop at that displacement, but it tends to move in the opposite direction until the kinetic energy is transformed into potential energy. That is, the distance it will move is until the energy under the loop in the second direction is equal to that in the initial direction. Therefore, if a structure has different energies required to get to yield in each direction, according to this theory, it should yield in the direction with the smallest energy. This is shown in Figure 13a. If only the stiffness, but not the strength is changed, as shown in Figure 13b, it would be expected that the structure would yield more in the stiffer direction because the energy required to get to the same yield displacement is lower.

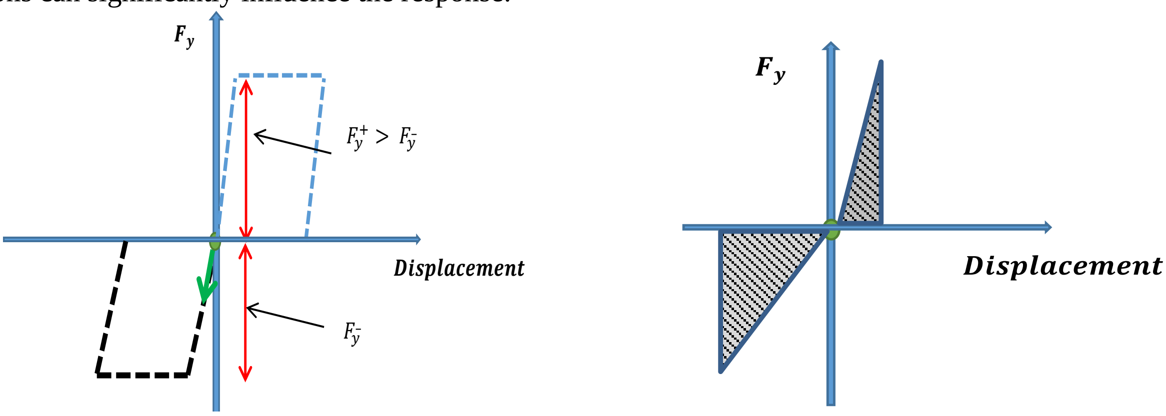
The actual response of the structure is complicated by two aspects:

1) The period of the structure in the stiffer direction is reduced.

The spectral displacement in the stiffer direction is therefore less than that in the weaker direction. This counters the tendency for greater displacements in the stiffer direction for oscillators with only the stiffness increased (and not the strength) as described above. Because the energy issue and the period issue are fighting each other, it may be the reason that the stiffness can have very little effect on the response, as described above.

2) The hysteresis loop shape

When there are several inelastic cycles of displacement, the different hysteretic characteristics in the different directions can significantly influence the response.



(a) Structure with different strength and stiffness (b) Energy of structure with different stiffness

Figure 13: Effect of strength and stiffness

7. Conclusion

A three story 2-D steel frame building structure was analyzed under a series of earthquake events using inelastic dynamic time history analysis to evaluate the feasibility of straightening buildings during aftershocks with tension braces. The residual inter-story drift ratio (RISDR) of the building after the first shake and then after additional shakes with different types of tension-only brace was investigated. This study shows that:

1. By increasing the story strength in the direction of deformation after the first shake, the residual inter-story drift ratio (RISDR) of the structure decreased. This concept can be used to straighten buildings with residual displacements using a later earthquake and protect them against further deformation in the same direction. However, with a high strength increase over-straightening may occur causing significant residual drifts in the opposite direction. The optimal increase of story strength of the structure was about 35% for these particular studies.
2. By increasing the story stiffness of the structure, the residual inter-story drift ratio (RISDR) of the structure first decreases, but then it starts to increase. It is less effective at controlling displacement than the use of displacement. The optimal increase of story stiffness of the structure was 10% for these particular studies.

8. Acknowledgement

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