Fling-step effect on the seismic behaviour of high-rise RC buildings during the Christchurch earthquake

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ABSTRACT: Fling-step and forward directivity, which can impose unexpected seismic demands on structures, are the main consequences of near-fault earthquakes. Although the adverse effect of forward directivity on structures behavior is determined to some level, the influence of fling-step (static offset) on the seismic response of structures has not been extensively investigated. Given the contradictory results reported in the few available studies, further investigation on the effect of fling-step on the seismic behavior of tall buildings seems important. To this end, the ground motion record at the Heathcoat Valley Primary School station from the 2011 New Zealand earthquake with fling-step has been selected. Subsequently, various single-degree-of-freedom systems with different fundamental period values have been considered and the displacement demands of each structure subjected to the ground motion record with and without fling-step have been investigated. The results show that the demands imposed on the structures without fling-step are relatively higher in some cases. It is shown that the amount of variability in the seismic demands can depend on the ration of the fundamental period of the structure to the period of the fling-pulse.

Keywords: near-fault, fling-step, structural performance, 2011 New Zealand earthquakes, RC buildings

1 INTRODUCTION

As a result of two near fault effects called “directivity” and “fling-step”, earthquake records that are near to the ruptured fault are importantly different from the ones observed further away from the causative fault. Directivity results from constructive interference of ground motions generated from different patches of slip located down strike for strike-slip faults or down dip for dip-slip faults (Abrahamson, 2001). Fling-step, on the other hand, is a strong velocity pulse which stems from the *permanent tectonic ground displacement* that corresponds to the amount of slip on the causative fault. The later effect has been observed in some near-fault ground motions such as in 1999 Kocaeli in Turkey (Sekiguchi and Iwata, 2002), 1999 Chi-Chi in Taiwan (Boore, 2001) and 2011 Tohoku in Japan (Suzuki et al., 2011). These types of ground motions may generate high demands that induce the structures to dissipate the input energy with few large displacement excursions. The inconsistencies reported in the results of the few papers investigating the fling-step effect on the structural behaviour of structures (Abrahamson, 2001; Lestuzzi et al., 2004; Kalkan and Kunnath, 2006; Ventura et al., 2011) create a research challenge to study the phenomena in more cases when possible.

The main objective of this article is to investigate the influence of "fling-step" effect on the seismic behaviour of RC long-period structures during the 2011 Christchurch earthquake. To this end, the ground motion record at the Heathcote Valley Primary School (HVSC) with fling-step has been used. Considering that SDOF systems play significant contribution in many research in the field of earthquake and structural engineering (e.g., Chopra and Chintanapakdee, 2001; Riddell et al., 2002; Mavroeidis et al., 2004; Dicleli and Buddaram, 2007), the non-linear structural behavior of RC buildings with respect to first fundamental mode is described by modified Takeda hysteretic model (Lestuzzi et al, 2007). The displacement ductility demand is considered as the indicator for the nonlinear seismic response. The response of different SDOF systems are calculated and discussed subsequently.

2 2010-11 CANTERBURY EARTHQUAKE AND NEAR-FAULT CHARACTERISTICS

2.1 Canterbury earthquake

On February 22, 2011 the M_w 6.2 Christchurch earthquake struck Christchurch approximately six months after the September 4, 2010 M_w 7.1 Darfield (Canterbury) earthquake. The earthquake was centred approximately 10-km south-east of the Christchurch central business district at a shallow depth of 5km (Kam et al., 2011). The earthquake killed more than 180 people, and damaged or destroyed more than 100,000 buildings. Those two earthquakes were the deadliest disaster in the country since the earthquake that struck the Napier and Hastings area on February 3, 1931 (Kalkan, 2011). In the September 4 earthquake, limited-to-moderate damage was observed in engineered RC buildings (Kam et al., 2010). In contrast, after the February 22 event, about 16% out of 833 RC buildings in the Christchurch CBD were severely damaged (Kam et al., 2011).

2.2 Near-fault characteristics

Near-fault ground motions have unique features than that of far fields. The strong velocity pulse resulting in forward directivity and fling-step effect is the main characteristic of such motions (Abrahamson, 2001; Lili et al., 2005). Fling-step is concerned with permanent tectonic displacement which is recognized as full sinusoidal pulse in acceleration diagram and half sinusoidal pulse in velocity diagram (Figure 1). During the February 22, 2011 earthquake, recorded peak ground acceleration (PGA) reached up to 2.2 g (vertical) and 1.7 g (horizontal) at Heathcoat Valley Primary School (HVSC) station (Kaiser et al. 2012). Raw data of the Christchurch earthquake at HVSC station (component S26W) was selected in this paper to study the effect of fling-step. The base line correction was applied to the record using a specific technique proposed by Iwan et al. (1985). Figure 2.a and 2.b show the base-line corrected acceleration and the extracted fling-step pulse of component S26W, respectively.

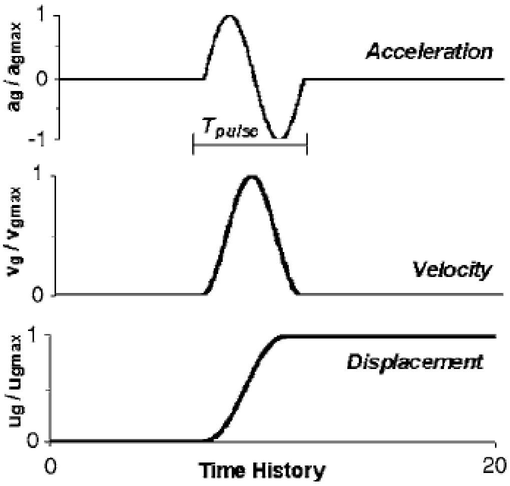
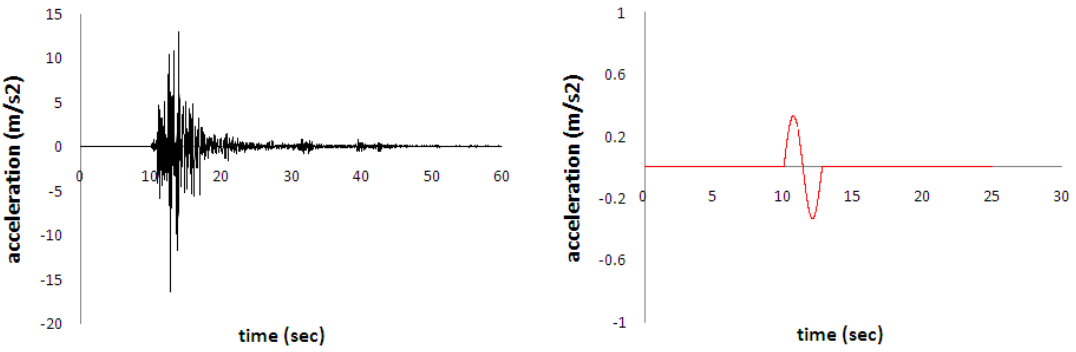


Figure 1. Representation of sinusoidal pulses (Kalkan and Kunnath, 2006)



a. HVSC (S26W) acceleration b. Extracted fling-pulse (T_{fling}= 2.75 sec)

Figure 2. Base-line corrected acceleration and extracted fling pulse

The extracted fling pulse from S26W component of the HVSC station corresponds to a permanent displacement of approximately 40 cm. Figure 3 demonstrates the displacement of HVSC-S26W component before and after removal of fling-step effect.

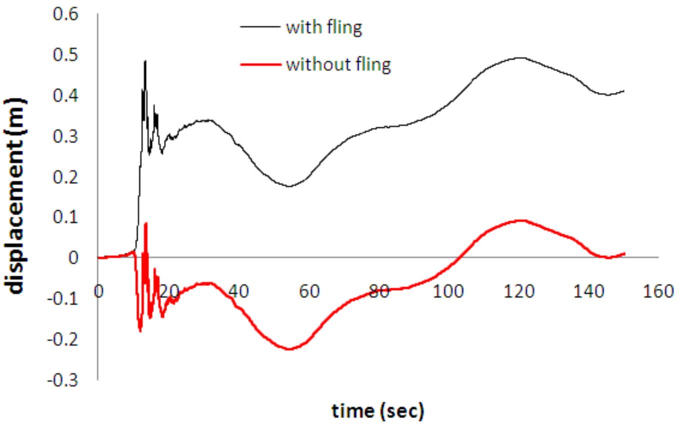


Figure 3. Displacement of HSVC-S26W component, before and after the removal of fling-step effect

3 RESPONSE OF SDOF SYSTEMS

A computer code was developed using MATLAB to calculate the nonlinear response of the single degree of freedom (SDOF) systems with various fundamental period of vibration subjected to the HVSC ground motion record with and without the fling-step.

3.1 Takeda model

The structural behavior of SDOF system in the nonlinear analyses is described by a modified Takeda hysteretic model which is an adequate model for concrete material (Figure 4). *Displacement Ductility Demand (DDD)*, as the representative indicator for result of nonlinear seismic response is considered. The effect of fling-step on the structural behavior of the SDOF systems are compared in two statuses: (i) with fling-step, and (ii) without fling-step.

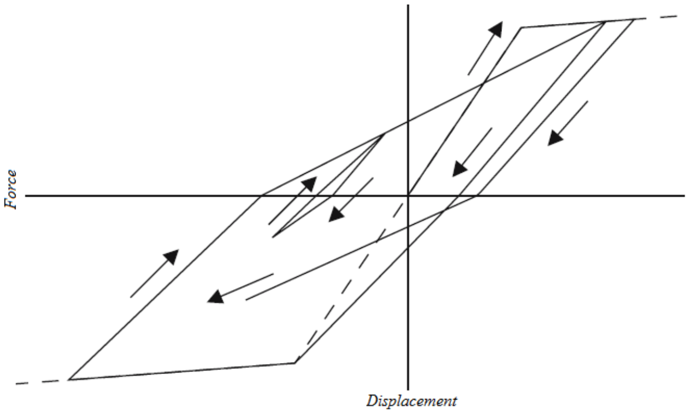


Figure 4. Modified Takeda model used in the analyses (Lestuzzi et al., 2007)

3.2 SDOF results

The analyses of the seismic responses were performed for various conditions including different fundamental periods (T_1=1.5, 2.0, 2.5, 3. 0, 3.5 and 4.0 sec) and different strength reduction factors (R=5~12). As an example, the results for the SDOF with T_1=2.0 sec and R=5 are shown in Figure 5. Given the value of strength reduction factor, yield-displacements were initially determined via a linear elastic analysis. Each SDOF system was subjected to the HVSC ground motion record (with fling-step) and the corresponding ductility demand was attained through nonlinear dynamic analysis. Subsequently, the effect of fling-step was removed from the primary waveforms and the same SDOF system was subjected to the new ground motion record (without fling-step).

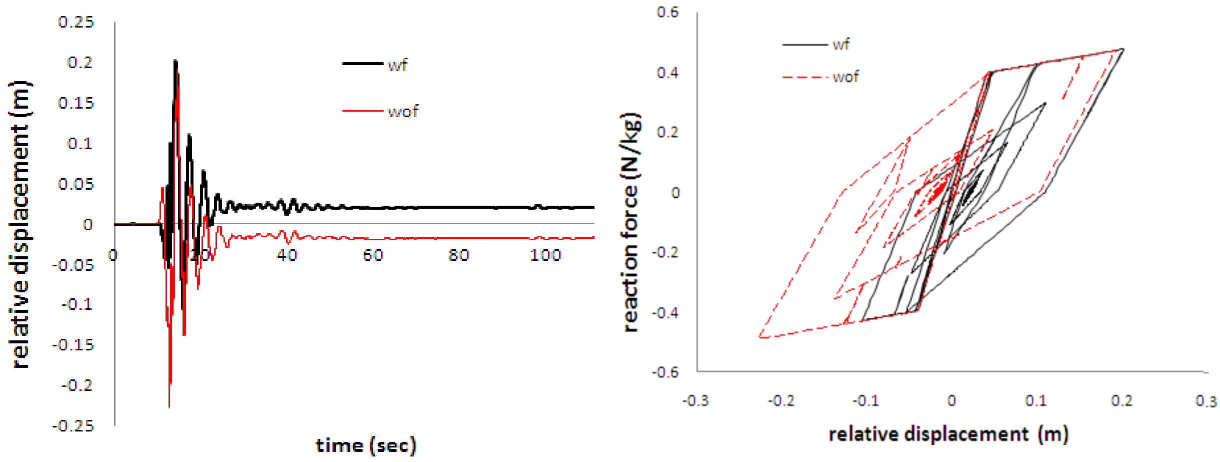
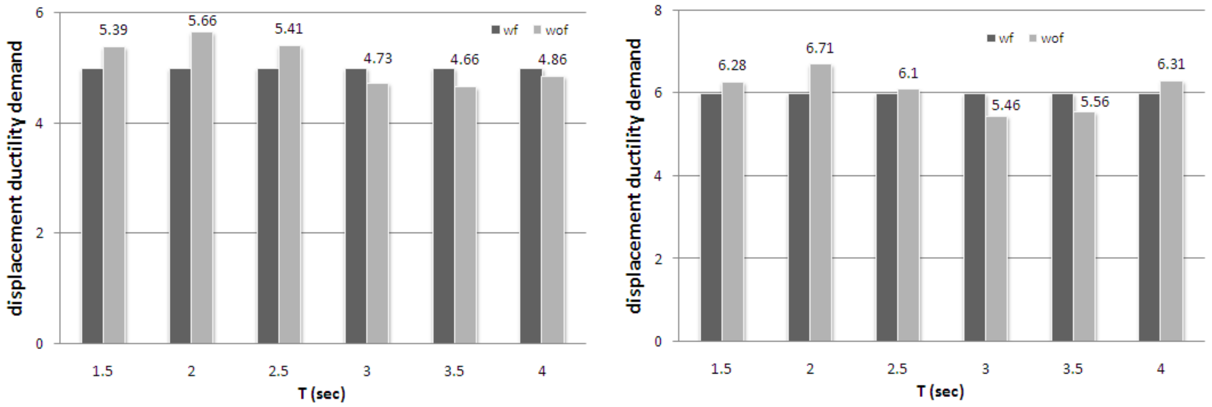


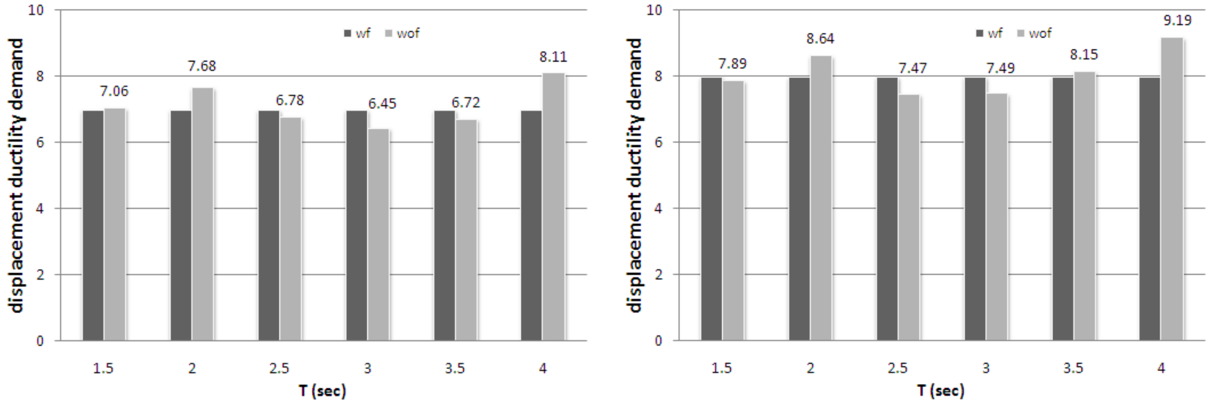
Figure 5. Comparison of response of SDOF (T_1=2.0 sec and R=5) to HVSC earthquake record with & without fling-step (wf: with fing-step; wof: without fling-step effect)

Figure 6 presents the displacement ductility demand in the SDOF systems as a function of the fundamental period of vibration with different values the strength reduction factor R.



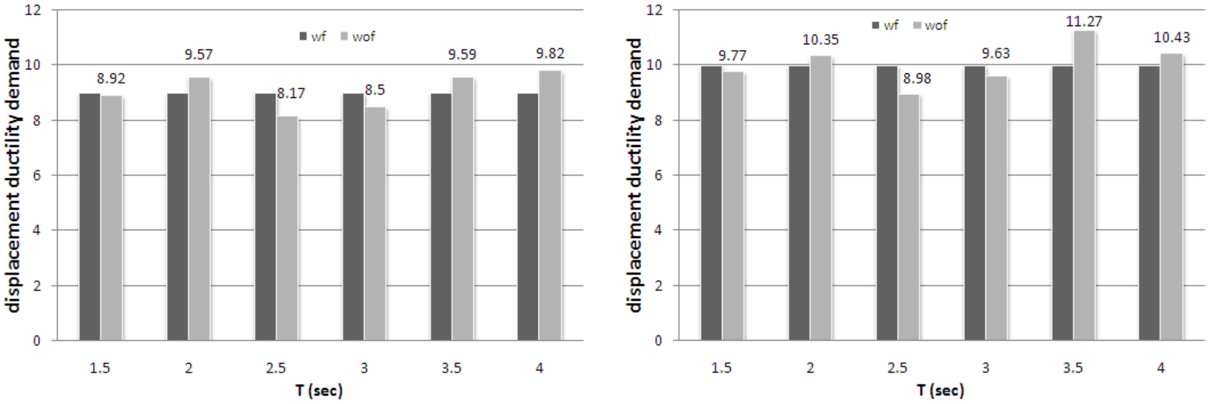
a. R=5

b. R=6

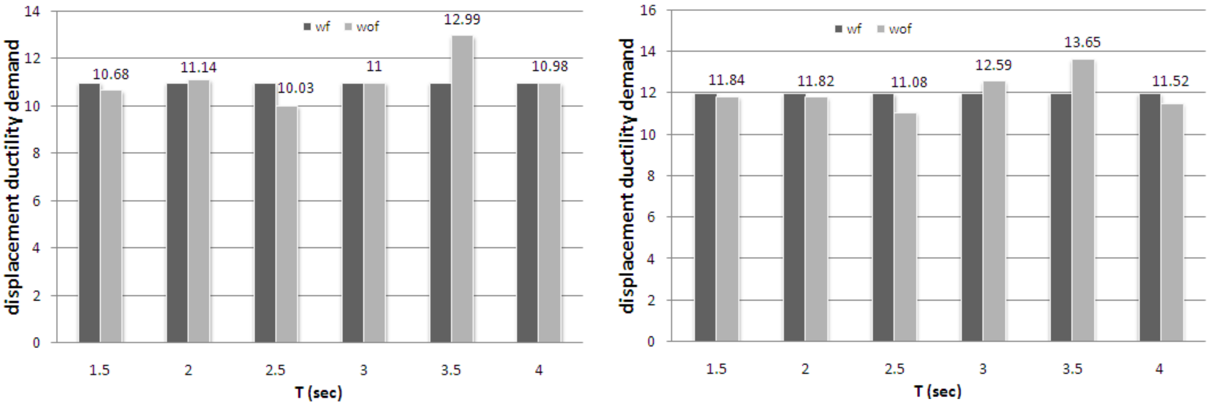


c. R=7

d. R=8



e. R=9 f. R=10



g. R=11 h. R=12

Figure 6. Displacement ductility demands in the SDOF for different values of the strength reduction factor and fundamental period with and without the fling-step

In Figure 6, for smaller natural period values ($T_1 < 2.5$ sec.) and lower strength reduction factors (R=5 or 6), the displacement ductility demand became generally higher when the fling-step was removed from the ground motion record meaning that the fling-step has been in favour of the structural seismic performance. However, according to the results shown in Figure 6, the responses of the SDOF systems subjected to the HVSC ground motion record show a mixed trend. While the displacement ductility demand for some SDOF systems was reduced when the fling-step phenomena existed, in some other cases, the displacement ductility demand was decreased when the fling-step was removed. Such mixed results are in line with the inconsistencies reported in some other studies performed on the effect of the fling-step (e.g., Ventura et al. 2011 and Kalkan and Kunnath 2006). If the T_{fling} is considered as a criterion, the displacement ductility demand seems to stay unchanged or decrease with the fling-step in the HVSC ground motion record (see Figure 2.b) for SDOF systems with $T_1 < T_{fling}$ in most cases.

4 CONCLUSION

We investigated the effect of fling-step on the response of high-rise buildings during the Christchurch 2011 earthquake. The study was conducted on SDOF systems representing high-rise buildings with different dynamic and structural properties (natural period of vibration and strength reduction factor). Each SDOF system was subjected to the ground motion recorded at the Heathcote Valley Primary School once with the fling-step effect (primary record) and then with the fling-step effect removed. The results showed an increase in the seismic demand for particular SDOF systems (smaller natural period values and lower reduction factors) when the effect of fling-step was removed from the primary ground motion. The amount of structural response depends on the ratio of the fling-pulse period to the fundamental period of the structure. The mixed results observed from the nonlinear dynamic analyses for the Christchurch earthquake is in line with the results reported in the literature regarding the effect of the fling-step on the structural performance of long-period buildings.

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